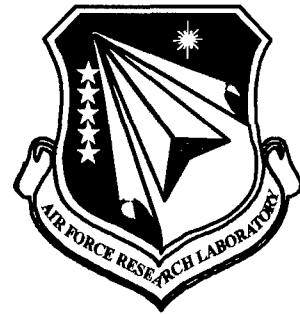


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**AIRCRAFT HANGAR FIRE THREAT
STUDY AND ANALYSIS**



**S.P. WELLS, K.S. COZART,
M.B. MITCHELL, R.D. DODSWORTH**

**HQ AFCEA /QI /CESM
TYNDALL AFB FL 32403**

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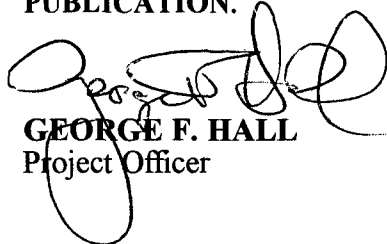
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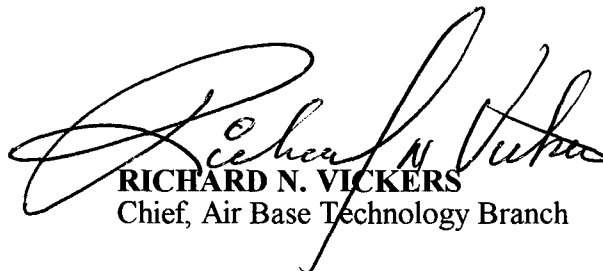


GEORGE F. HALL
Project Officer

FOR THE COMMANDER:



ALLEN D. NEASE
Chief, Infrastructure Technology Section



RICHARD N. VICKERS
Chief, Air Base Technology Branch

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PREFACE

This report was prepared by the Air Force Research Laboratory Air Base Technology Branch, Tyndall Air Force Base, Florida 32403.

Lt. Col. Craig Mallerski, HQ AFCESA/QI, was the Project Manager. Mr. Fred K. Walker, HQ AFCESA/CESM, was the Technical Advisor. This test program was completed in support of HQ AFCESA. This report presents the results of the Aircraft Hangar Fire Threat Study and Analysis.

This report has been reviewed and is approved.

EXECUTIVE SUMMARY

A. OBJECTIVE

Headquarters Air Force Civil Engineer Support Agency (AFCESA) tasked the Air Force Research Laboratory Fire Research Group, AFRL/MLQC, to evaluate the current fire threat in aircraft hangars based on the presently used aviation fuels. This threat analysis will be used to structure a test program to evaluate a variety of fire suppression and control concepts to determine the most appropriate systems to ensure maximum mission continuity at a minimum life-cycle cost. These requirements, developed during subsequent phases, will be fielded in standardized handbooks for the engineering flight, design and construction agents, and architect and engineering firm use.

B. BACKGROUND

Current aircraft hangars and fire extinguishing systems were designed and built during a period when aviation gasoline (Avgas) and JP-4 were the predominant aircraft propulsion fuels. Avgas is highly volatile, propagating at an explosive rate when ignited. JP-4 is also highly volatile. Compounding this situation, aircraft undergoing maintenance during that earlier period were not completely de-fueled. As a result of these factors, hangar electrical systems were designed to meet Class I, Division II requirements, and fire suppression systems were designed to respond to incipient explosions and rapidly propagating fires. Today, the predominant fuels now in use are Jet-A in commercial aircraft and JP-8 in military aircraft. These fuels are much more difficult to ignite, and when ignited the flames spread at a much slower rate. These factors result in what appears to be a significant reduction in the fire threat.

Another major factor contributing to the current design of fire suppression systems was the postulated fuel spill fire scenario. Most aircraft hangar fire threat analyses performed to date have been based on the energy release profiles from deep pool fires. In reality, hangar mishaps result in fuel being spilled on a relatively flat concrete surface. JP fuel spilled on a flat surface will seek an equilibrium depth of less than 1/8 inch. Since JP-8 fuel burns at a rate of approximately 1/8 inch per minute, the fire at any given location will consume its available fuel supply and burn out much faster than a pool fire. Consequently, for large spills of low-volatility fuels on a concrete surface, the intensity of the fire over time is much less than that of a pool fire.

C. SCOPE

This study evaluated the fire threat associated with the use of JP-8 as compared to the fire threat associated with the use of JP-4 during normal hangar aircraft maintenance operations. Evaluations included fuel ignition sources, flame spread, flat-plate fuel spills and fire energy releases. The fire threats not evaluated in this study are those associated with specialized hangar aircraft maintenance operation such as corrosion control facilities (e.g. spray painting operations), hangars in which refueling operations occur (where there is a potential for an atomized fuel spray), and fuel cell repair.

JP-4, JP-8 and JP-5 fuels were tested in the analytical chemistry facility walk-in hood to determine the ignition characteristics for each when exposed to an electrical arc and a flame. The fuels were tested for vapor ignition height above the surface of a fuel spill. Flame spread rate tests were also conducted in the walk-in hood. Flame spread tests were conducted in a controlled temperature V-shaped trough of dimensions two-inches wide, three feet long with two-inch sides. Fuel temperatures were varied from 80°F to 160°F for all of the above tests.

JP-4 and JP-8 were evaluated at Test Range I and Test Range II for ignition characteristics when exposed to hazardous electrical tools and equipment, welding and acetylene cutting operations, electrical arcs and ignited matches. The test setup and results are located in Appendix I.

Flat-plate fire intensity tests were conducted inside of a Third-Generation Aircraft Shelter, with a 30 foot high ceiling. Fuels were spilled and burned inside a 20' X 18' steel test pan on an 18' X 18', four inch thick concrete pad. These tests evaluated JP-4, JP-8 and JP-5 flat-plate fuel spills and fires. Temperature and heat flux data was collected and analyzed to compare fire intensities.

D. CONCLUSIONS

The threat of a JP-8 fuel spill ignition in an Air Force hangar is greatly reduced when compared to the previous threat from JP-4 fuel. Under ambient hangar conditions (floor temperatures 60° - 90°F) an ambient JP-8 fuel spill produces insufficient vapors to support ignition. This is to say that JP-8 must be subjected to a sustained heat source in order to produce the vapors required for ignition. This makes the fuel safer from an ignition standpoint, and from a flame spread standpoint an ambient JP-8 fuel spill can require a significant time (20-30 seconds) to build up the thermal flux necessary to increase the flame spread rate. While JP-4 grows to its full extent within a few seconds after ignition leaving a maintenance operator little time to respond, the JP-8 spill fire remains in its incipient stage 20-30 seconds after ignition allowing maintenance personnel time to react.

There is no prominent difference in the fire intensity of JP-4, JP-8 and JP-5 flat-plate fires once they reach full intensity. The main difference in the way the fuels burn is due to flame spread and fire growth rate. When the fuel fires achieve maximum intensity, heat flux and temperature measurements for the fuels are similar.

The inherent safety of JP-8, however, can cause individuals to become complacent in adhering to safety practices. NFPA 70, National Electric Code⁶, requires electrical connections, conduit, equipment, tools, heaters, and motors to comply with Class I, Division II locations in Air Force hangars. Although JP-8 is a safer fuel than JP-4, safety practices, like those in the NFPA and OSHA guidelines that can prevent possible fuel ignition sources should continue to be followed. Continuing fire safety education on the use of equipment and procedures for workers in Air Force hangars will result in a fire safe environment.

SECTION I

INTRODUCTION

A. SCOPE

This test program evaluated, on a small scale, the fire threat in Air Force hangars from JP-8 fuel. This study was initiated to determine the fire threat associated with the use of JP-8 as compared to the fire threat associated with the use of JP-4 during normal hangar aircraft maintenance operations. Evaluations included fuel ignition sources, flame spread, flat-plate fuel spills and fire energy releases. The fire threats not evaluated in this study are associated with specialized hangar aircraft maintenance operation such as corrosion control facilities (i.e. spray painting operations), hangars in which refueling operations occur (where there is a potential for an atomized fuel spray), and fuel cell repair. Tests were conducted by the Air Force Research Laboratory Fire Research Group AFRL/MLQC at Test Range II and at the analytical chemistry facility located on Tyndall AFB, Florida.

B. BACKGROUND

Current aircraft hangars and fire extinguishing systems were designed and built during a period when aviation gasoline (Avgas) and JP-4 were the predominant aircraft propulsion fuels. Avgas is highly volatile, propagating at an explosive rate when ignited. JP-4 is also highly volatile. Compounding this situation, aircraft undergoing maintenance during that earlier period were not completely de-fueled. As a result of these factors, hangar electrical systems were designed to meet Class I, Division II requirements, and fire suppression systems were designed to respond to incipient explosions and rapidly propagating fires. Today, the predominant fuels now in use are Jet-A in commercial aircraft and JP-8 in military aircraft. These fuels are much more difficult to ignite, and when ignited the flames spread at a much slower rate. These factors result in what appears to be a significant reduction in the fire threat.

Another major factor contributing to the current design of fire suppression systems was the postulated fuel spill fire scenario. Most aircraft hangar fire threat analyses performed to date have been based on the energy release profiles from deep pool fires. In reality, hangar mishaps result in fuel being spilled on a relatively flat concrete surface. JP fuel spilled on a flat surface will seek an equilibrium depth of less than 1/8 inch. Since JP-8 fuel burns at a rate of approximately 1/8 inch per minute, the fire at any given location will consume its available fuel supply and burn out much faster than a pool fire. Consequently, for large spills of low-volatility fuels on a concrete surface, the intensity of the fire over time is much less than that of a pool fire.

C. PURPOSE

The Headquarters Air Force Civil Engineer Support Agency (AFCESA) is evaluating the current fire threat in aircraft hangars based on the presently used aviation fuels. This threat analysis will be used to structure a test program to evaluate a variety of fire suppression and

control concepts to determine the most appropriate systems to ensure maximum mission continuity at a minimal life-cycle cost. These requirements developed during subsequent phases will be fielded in standardized handbooks for the engineering flight, design and construction agencies, and architect and engineering firm use.

D. APPROACH

Tests were conducted in the Air Force Research Laboratory analytical chemistry facility to compare fuel vapor ignition of JP-4, JP-8, and JP-5 when exposed to a spark ignition source and a flame ignition source. These liquid fuels are composed of numerous hydrocarbon molecules which have varying vaporization temperatures. When these fuel molecules vaporize and concentrate above a fuel spill, a flammable gas mixture can form. The flash point of the fuels is the temperature at which the vaporized fuel molecules form a flammable, or lower explosive limit (LEL), mixture above the spill. Fuel composition and flash point data is listed in the discussion on fuels in Section II.

In a study conducted to determine the fuel vapor hazards from fuel spills in hangars, Eggleston and Pish¹ established that, "The vapor concentrations in the spill area are determined by an equilibrium between the quantity of vapor evolved and the rapidity with which it is swept away and diluted by air currents." For JP-4 they conclude that the maximum height above a fuel spill that a flammable vapor concentration will form in a hangar is seven inches and even small air currents will reduce the height above a spill of these flammable vapor concentrations. These air currents can be caused by common phenomena such as wind through open passages or by convection due to temperature variations in the room. As a result, JP-4 fuel vapor ignition would not be expected above a six-inch level for ambient temperatures of 100°F or below. JP-8 and JP-5 were not tested in the Eggleston and Pish¹ study, however, these fuels have flash points above 100°F and do not form flammable vapor mixtures below this temperature.

In maintenance hangars it is not likely that fuel temperatures will exceed 110°F, however hangar fuel temperatures were not evaluated in this study. The following are possible reasons for elevated fuel temperatures: 1) JP-8 fuel is used as an oil coolant during flight and fuel temperatures in-flight exceed 160°F on-board aircraft, 2) there is a possibility of solar heating of fuel tanks on the flightline prior to aircraft maintenance, 3) ambient temperatures could exceed the fuel's flash point. Fuel vapor ignition of JP-4, JP-8 and JP-5 was characterized in this study for fuel temperatures of 75° - 165°F. A majority of the tests were conducted in the analytical chemistry facility to compare the previously studied JP-4 to JP-8 and JP-5 fuel vapor ignition from a high-voltage spark, from a flame, and ignition by a hot surface.

After a fuel spill occurs in a hangar and the fuel ignites, flame spread and fire intensity contribute to the hazard associated with each jet fuel. Flame spread across the surface of the fuel spill after ignition determines how fast a fire reaches full intensity where it may cause damage to an aircraft or structure, and it determines necessary fire department or suppression system response time. Flame spread was measured in laboratory analysis and noted during small-scale tests. Fire intensity measurements of these fuels were taken during small-scale tests conducted at Test Range II.

SECTION II

TEST PROTOCOL

A. GENERAL

AFRL/MLQC conducted technical experiments and evaluations to quantify the ignition characteristics, flame spread velocity, and energy release (temperature and thermal flux), for flat-surface fuel spills of JP-8, JP-5, and JP-4. These tests were conducted on a laboratory scale and small scale (325 ft² concrete surface representative of a typical hangar floor). Certain aircraft utilize the on-board fuel supply as a heat sink for oil, and fuel temperatures can approach 165°F. Since the surface tension and volatility of the fuel vary with temperature, the effects of fuel temperature on flame spread and fuel ignition were also investigated.

B. FUELS

The fuels evaluated in this test series were JP-4, JP-8 and JP-5. The highly volatile JP-4 was the predominant aircraft fuel when current aircraft hangars and fire suppression systems were designed and installed. Today, JP-8 is the predominant fuel in use by the Air Force and JP-5 is the principal fuel in use by the Navy.

Composition

These fuels are composed of a mixture of additives and hydrocarbon molecules which give the fuels their individual properties. The hydrocarbon components of the fuel are classified by the number of carbon atoms in the component (carbon number). The lower the carbon number of a component, the lighter the molecule. This in turn corresponds to a lower boiling point and a lower flash point.

Simulated distillation is a chromatographic technique for analysis of petroleum fractions which separates the constituents of the fraction according to boiling points or carbon number. A chromatographic detector records the separation of the constituents and the amounts. Using this method, the distribution of hydrocarbons in jet fuels has been determined². This is shown in the graphs of Figure 1.

The flammability of a fuel at a defined temperature is based on the flammable characteristics of its individual components at that temperature and on the percentage of the individual fractions in the fuel. For example, the flammability of a fuel at room temperature is determined by the percentage of fractions with flash points equal to, or below, room temperature. Fractions with a carbon number of C7 or lower meet this criteria. Table 1 shows some general properties of hydrocarbon molecules with three to seven carbon atoms and the percentage of these in JP-4, JP-8 and JP-5.

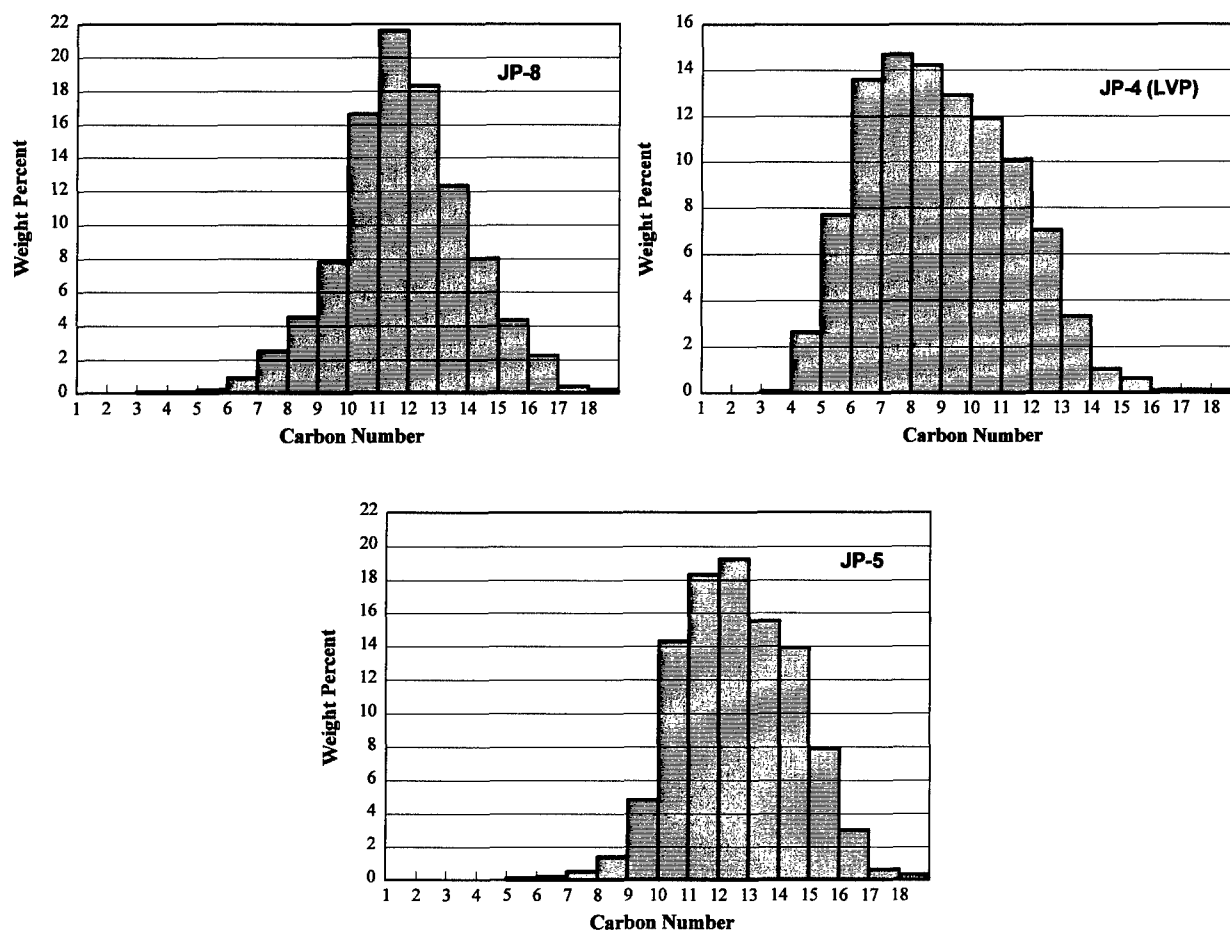


Figure 1: Distribution of Hydrocarbons in Jet Fuels Determined by Distillation²

The total amount of material in JP-4 which is readily flammable at room temperature is 38.7%; in JP-8 it is 3.8% and JP-5 it is 0.8%. JP-4 has a low closed-cup flash point because almost 40% of its composition consists of C7 material and below. Since JP-8 has only about 4% of its composition made up of C7 and below and JP-5 has less than 1 %, they do not form a flammable vapor mixture or burn readily at room temperature.

Table 1
Room Temperature Fuel Flammability Factors

Carbon Number	Boiling Point	Flash Point	JP-4 %	JP-8 %	JP-5 %
C3-C4	< 32°F	< -58°F (< - 50°C)	2.7	0.2	0.0
C5	97°F (36°C)	< - 40°F (< - 40°C)	7.7	0.2	0.1
C6	156°F (69°C)	- 8°F (- 22°C)	13.6	0.9	0.2
C7	208°F (98°C)	25°F (- 4°C)	14.7	2.5	0.5
C3-C7 Total			38.7	3.8	0.8

Vapor Pressure

Van der Waals forces are the forces which hold non-polar molecules together in the liquid phase. They are weak and of short range. The larger the surface area of a given molecule, the stronger those van der Waals forces are. Therefore, an increase in molecular size, or an increase in the carbon number, i.e. C5, C6, C7 (pentane, hexane, heptane), causes an increase in the Van der Waals forces.

For a molecule to leave the liquid phase and enter the vapor phase, it must have the energy to overcome the van der Waals forces and the force of surface tension. This energy is the energy of motion caused by temperature. Thus, increasing the temperature will cause an increase in the number of a given type of molecule entering in the vapor phase, depending upon its molecular size. As increasing numbers of molecules enter the vapor phase, the vapor pressure of a fuel increases. Fuel properties are listed in Table 2. Vapor pressures for JP-4, JP-8 and JP-5 are plotted in Graph 3.

Table 2
Fuel Properties

	JP-8	JP-4	JP-5
Published Minimum Flash Point⁵	100°F (38°C)	-10°F (-23°C)	140°F (60°C)
Measured Flash Point	110°F (43°C)	n/a	140°F (60°C)
Published Fuel Density @ 77°F (25°C)²	798 kG/m ³	749 kG/m ³	805 kG/m ³
Measured Fuel Density @ 79°F (26°C)	779 kG/m ³	778 kG/m ³	795 kG/m ³

C. IGNITION CHARACTERISTICS

Electrical Arc and Flame Ignition Tests

JP-4, JP-8 and JP-5 fuels were tested in the analytical chemistry facility walk-in hood to determine the ignition characteristics for each when exposed to an electrical arc and a flame. The fuels were tested for vapor ignition height above the surface of a fuel spill. Fuel temperatures for these tests ranged from 80° to 160°F. The fuels were not expected to ignite below their individual flash points. For both test scenarios, a 12" X 12" stainless steel spill pan was located on a 12" X 12" electrical panel heater. When heated fuel was required, a magnetic stirrer hot plate was used to heat the fuel before the test and the electrical panel heater was used to heat the pan to the same temperature. Pan heating was required for maintaining constant fuel temperature throughout the test. At the beginning of the test 600ml of fuel were poured into the pan. The pan was cleaned between each test and fresh fuel was added for each test.

A 10,000 V spark plug provided the electrical arc for fuel ignition during the spark ignition tests. The spark plug was located on the end of a vertically telescoping arm, 15 inches above the test pan. After the fuel was poured into the pan, fuel temperatures were recorded.

These temperatures were manually recorded due to the hazards of high voltage to the data acquisition system. The spark ignitor was lowered at 0.5 in/s towards the spilled fuel (see Figure 2). When the fuel vapors ignited, the ignitor was stopped and the flames were extinguished. The height of the spark was then recorded. In the cases where low volatility fuels were tested below their flash point, the ignitor was lowered into the fuel spill to determine if ignition would occur due to localized heating of the fuel.

Flame ignition tests were conducted in the analytical chemistry facility in much the same way as the spark ignition. A propane heating torch bottle was mounted on a vertically telescoping arm. The air inlet and the regulating valve on the torch were restricted to produce a one-inch high, 1800°F flame. Figure 3 shows the torch as it is lowered toward the fuel. Fuel temperature and ambient temperature above the fuel were measured with thermocouples and recorded with Strawberry Tree data acquisition hardware and software throughout each test. When the fuel vapors ignited, the fire was extinguished and the propane flame height was recorded.

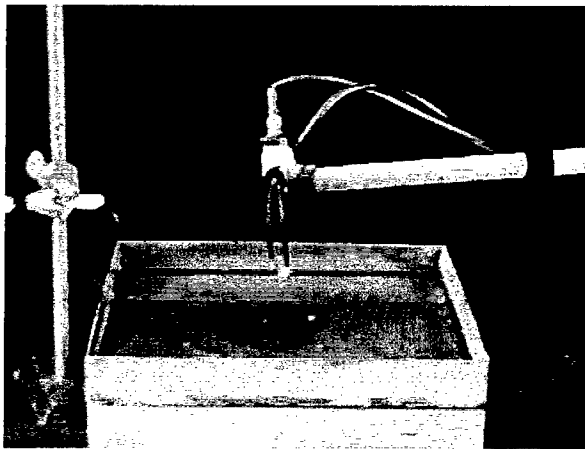


Figure 2
Spark Ignition



Figure 3
Flame Ignition

Hot Surface Ignition

Ignition of fuels can occur on hot surfaces, such as an exhaust manifold, where spark and flame ignition sources are not present. In aircraft maintenance hangars, surface temperatures sufficient to cause ignition can be found on aircraft ground equipment exhaust. However, most ground equipment with hot exhaust is not allowed to operate inside a hangar. Ignition of the fuel on a hot surface is determined by surface temperature, mass of the surface, fuel spill amount and air currents. The fuel will ignite most readily when a small amount of fuel is spilled onto a large hot surface in zero wind conditions.

Hot surface ignition tests of JP-4, JP-8 and JP-5 were conducted in a laboratory hood. In this test series, a 2" X 2" X 1" high stainless steel cup was mounted on a ring stand. A thermocouple measured the temperature of the cup in degrees centigrade. The cup was heated

by a Meker burner to 10°C above the desired test temperature. The burner flame height was reduced to eliminate it as an ignition source. The pan temperature then began to slowly decrease and when at the desired temperature, a drop of room temperature fuel was placed into the pan. Pan temperature, fuel type and ignition/non-ignition were recorded.

Field Ignition Tests

JP-4 and JP-8 were evaluated at Test Range I and Test Range II for ignition characteristics when exposed to a variety of hazardous electrical tools and equipment, welding and acetylene cutting operations, electrical arcs and ignited matches. The test setup and results are located in Appendix I.

D. FLAME SPREAD

Flame spread tests were conducted in the analytical chemistry facility, and observations of flame spread were noted during small scale tests. JP-4 fuel has a much higher flame spread rate than JP-8 or JP-5 between temperatures of 10° - 100°F. At these temperatures JP-4 is above its flash point and naturally emits flammable vapors, while JP-8 and JP-5 are still below their flash point and require heating to emit vapors. When the fuel temperature is increased above the flash point, the rate of flame spread of JP-8 and JP-5 increases.

Laboratory tests were conducted in a controlled temperature V-shaped trough of dimensions two inches wide, three feet long with two-inch sides. Figure 4 shows flame spread test 5. The trough was located in the analytical chemistry facility walk-in hood. The exhaust fan in the hood was only operated before and after the tests to reduce any effects of air currents. Fuel was spilled into the trough to within ¼ inch of the lip. Temperature of the fuel and fire propagation rate were measured with K-type thermocouples at a sampling rate of 50 Hz. Flame thermocouples were positioned 500mm apart and measurements were made 10mm above the surface of the fuel as the flame passed that point.

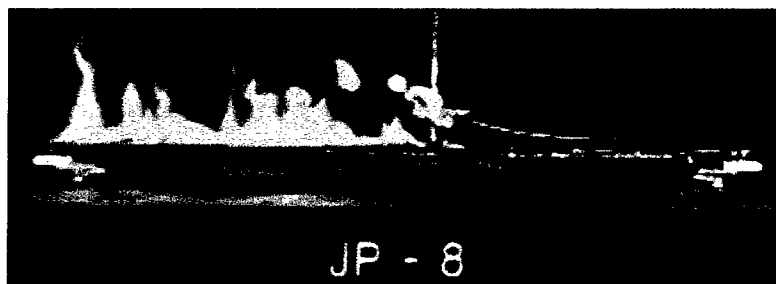


Figure 4
Laboratory Flame Spread Rate Test

For tests conducted above room temperature, the trough temperature was controlled with rubber heating tape attached to the outside of the trough. The fuel to be tested was heated separately, enclosed in a graduated cylinder. The fuel was poured into the trough one minute

before ignition. The fuel was ignited at one end of the trough with a propane ignitor and allowed to propagate to the other end of the trough before being extinguished.

Flame spread during small-scale tests conducted at Test Range II was compared to the laboratory results. Fuel was spilled onto a concrete surface with a grid of one foot squares (see Figure 5). Analysis of video from these tests allowed a comparison of these large fuel spill flame spread rates to the laboratory flame spread rates.

E. FIRE INTENSITY

Energy release tests were conducted inside of a Third Generation Aircraft Shelter, with a 30-foot high ceiling. Fuels were spilled and burned inside a 20' X 18' steel test pan on an 18' X 18', four inch thick concrete pad. These tests evaluated flat-plate fuel spill fires of JP-4, JP-8 and JP-5. The concrete pad was painted with a one foot square grid across the surface for determining fuel spill size. Figure 5 shows the grid layout and a typical five gallon fuel spill.

Many studies have been conducted on pool-fire energy release, however, the geometry of the pool-fire tests are different than flat-plate tests. Pool fires are usually conducted inside of a steel pan with a deep layer of fuel that allows burn times greater than four minutes. Additionally, the fuel is floated on a layer of water inside the test pan. A more realistic hangar fire scenario is a flat-plate spill fire because these tests allow the fuel to seek an equilibrium depth on a concrete surface which allows for shorter burn times. Also, when burning, the fuel is in contact with a concrete surface rather than a layer of water.

Before each test, fuel temperatures, concrete pad temperatures and ambient temperatures were recorded. Fuel was spilled onto the concrete pad through a 1" ID pipe from five feet above the pad. After spilling the fuel, the fuel spill coverage was recorded on test data sheets. The fuel was ignited with a propane heating torch on the south side of the fuel spill for the two-gallon spills and on the west side of the spill for the five-gallon spills. Analog data was acquired with a PC-based data acquisition system and portable thermocouple recorders. A Daqbook Notebook data acquisition system with plug-in thermocouple and analog data acquisition cards and portable Omega OM-170 data recorders were used to retrieve data. Labview software and Omega software were used to process the data on a 486 computer. All data files were compatible with Microsoft Excel.

Directional Flame Thermometers (DFT) were located in the flame zone to measure 'hot wall heat flux'⁷ or radiating temperatures. These sensors are a type of thin-skin calorimeter developed by M. H. Burgess and C. J. Fry⁷ and manufactured by Ktech Corporation. They are constructed by attaching a thermocouple to a metal plate of known thickness(L), specific heat (C_p), and density(ρ). Heat flux (q_{plate}) is calculated by measuring the temperature change of the metal plate (dT_{plate}/dt) and applying the following formula:

$$q_{plate} = \rho C_p L (dT_{plate}/dt) \quad (1)$$

Two sensors on each DFT calorimeter faced opposite directions. These sensors were positioned facing north and south for all tests. In addition, two thin-skin calorimeters were positioned outside of the flame zone facing north into the fire during three of the five-gallon fuel spill fires. They were located four feet away from the edge of the fuel spill (see Figure 5) and 11 feet from the center of the fuel spill. Data was collected from these sensors as plate temperatures and were converted to kW/m^2 units.

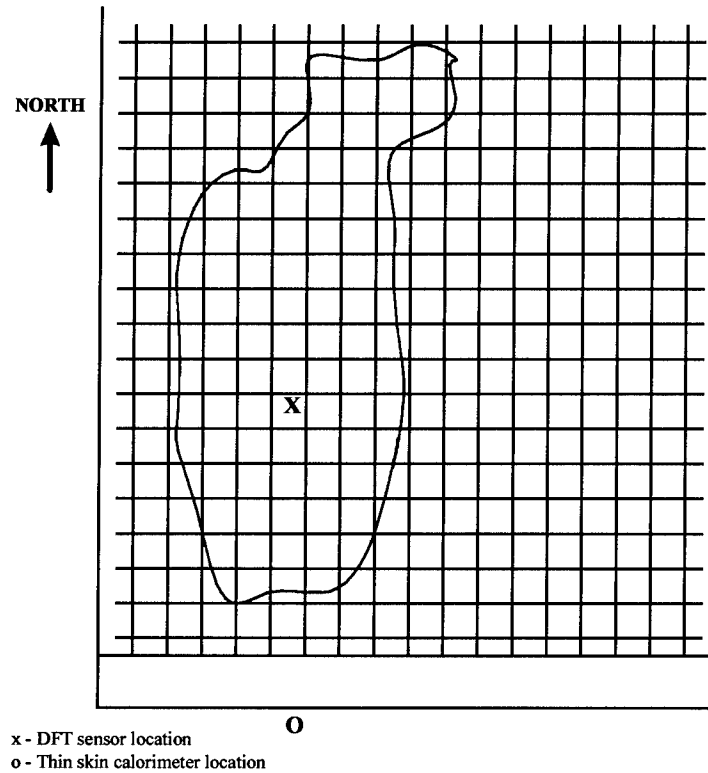


Figure 5

Concrete Pad with Heat Flux Sensor Locations & Typical Five-Gallon Fuel Spill

These DFT sensors, constructed of thin stainless steel, have a low heat capacity, similar to materials found in an aircraft fuselage. Therefore, the DFTs respond to flame similar to the way an aircraft would respond to flame. If exposed to flame for long periods, the measured 'hot wall heat flux' will approach zero as the sensor temperature approaches the flame temperature. These sensors worked well in this test program where they were exposed to short duration flames.

Two-gallon fuel spills were found to cover, on average, a 47 ft^2 surface area, and the resulting fuel fires grew to continuous heights of 18 feet. This size fuel spill was chosen for energy release tests. K-type inconel sheathed thermocouples were used to record temperatures in $^{\circ}\text{F}$. Thermocouples were positioned to measure concrete pad temperatures, fuel temperatures, flame temperatures above the pad, and ceiling temperature. Concrete temperature measurements were made with a sheathed thermocouple embedded one-half inch into the concrete surface. Fuel temperatures were measured before the test, at the discharge nozzle as fuel was spilled and

on the concrete surface during the test. DFT heat flux measurements were made at 7.5 and 15 feet above the surface of the spill. Thermocouples were positioned three inches from the sensor plates for all tests. Since the plume center moved during the tests, the sensors were positioned to be in and near the flame as much as possible. A thermocouple near the ceiling height was positioned 23 feet above the center of the test pan.

Five-gallon fuel spill sizes were selected for additional energy release tests since the resulting fire sizes were the maximum possible to obtain good results in the 30-foot high test facility. Larger fires produced a significant gas and smoke layer trapped under the ceiling of the facility. This hot gas layer will affect the fire plume, and this effect was seen during the latter stages of some of the five-gallon spill tests. The heat flux and thermocouple sensors located at 15 feet above the fuel spill in the two-gallon fuel spill tests did not collect much data due to the unpredictable fire plume. These sensors were moved to a height of 3.8 feet above the fuel spill for all but two of the five-gallon fuel spill fire tests. The sensors at 7.5 feet were left in place.

SECTION III

TEST METHODOLOGY AND RESULTS

A. IGNITION CHARACTERISTICS

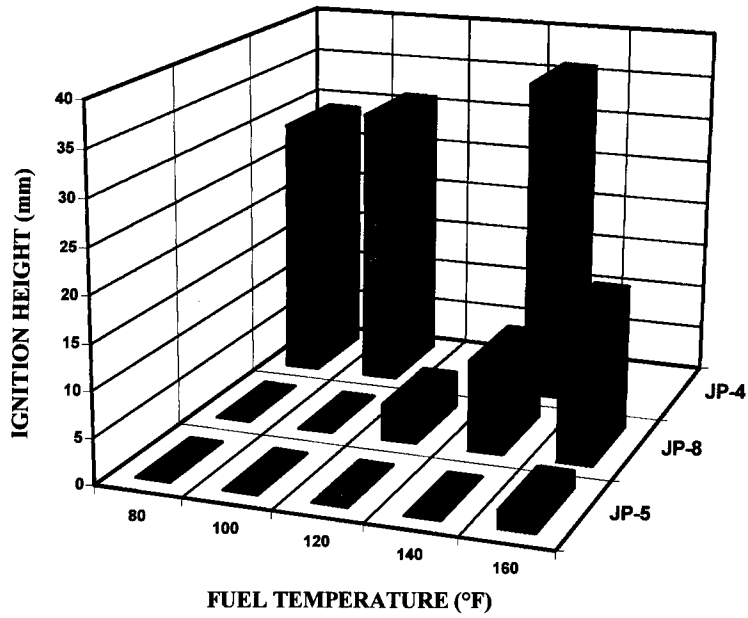
Electrical Arc Ignition Tests

Spark ignition tests were conducted in the analytical chemistry facility on JP-4, JP-8 and JP-5. The fuels were tested at room temperature and were heated to higher temperatures to simulate the threat of heated fuel spills in hangars. Fuel was spilled in a 12" X 12" pan for the tests. JP-8 and JP-5 were tested at temperatures up to 160°F. Results of these tests are shown in Graphs 1 and 2. Three tests were conducted within $\pm 4^\circ\text{F}$ (2°C) of the temperatures shown on the graph except for JP-5 which was tested once at 80°, 100°, and 120°F due to its high flash point. JP-4 was tested at temperatures of 80°, 100° and 140°F. These tests showed the fuels' flash point and vapor pressure properties in realistic, physical, hazard terms.

Ignition of the fuel vapors above the surface of a fuel spill is dependent on four factors: fuel vapor pressure (which is temperature dependent), surface area of the spill, air currents, and the effective dissipation of the fuels' volatile fractions¹. The effects of fuel volatile dissipation was minimized in all tests by keeping the fuel enclosed in a container until the beginning of the test. Air currents were minimized by conducting the test in a closed, walk-in hood with the air blowers turned off, and the surface area of the spill was constant for each test at 1 square foot. In these tests it was expected that ignition would occur at increasing height above the fuel spill as the fuel temperature increased, due to the effects of vapor pressure,. Graph 3 is a plot of vapor pressures for the three fuels as a function of temperature.

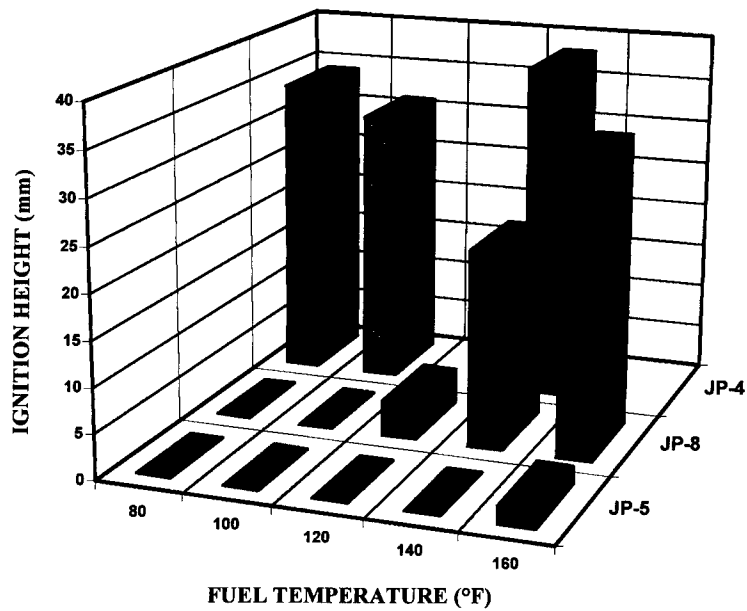
JP-4 fuel vapors ignited at room temperature and above. Graph 1 shows that the threat of igniting JP-8 or JP-5 vapors above a fuel spill with an electrical arc is non-existent below their respective flash points ($\text{JP-8} \geq 100^\circ\text{F}$, $\text{JP-5} \geq 140^\circ\text{F}$). JP-8 fuel vapors ignited above the surface of the spill at temperatures of 120°F and above. JP-5 fuel vapors ignited at 160°F. Graph 1 shows the average height of ignition for JP-8 at each temperature, however two data points stood out. Graph 2 shows the *peak* ignition heights for the three fuels. Graph 2 shows a JP-8 ignition at 22 mm above the surface at a temperature of 140°F and one at 33 mm above the surface at 160°F were more than three times higher than the averages at those temperatures.

Convection air currents produced from fuel temperatures higher than ambient temperatures may have affected fuel vapor ignition. As mentioned above, air currents can dissipate fuel vapors resulting in lower ignition heights than if no air currents were present. For this reason, the highest, or peak, levels of ignition above the spill are included in Graph 2 for comparison to average vapor ignition heights in Graph 1.



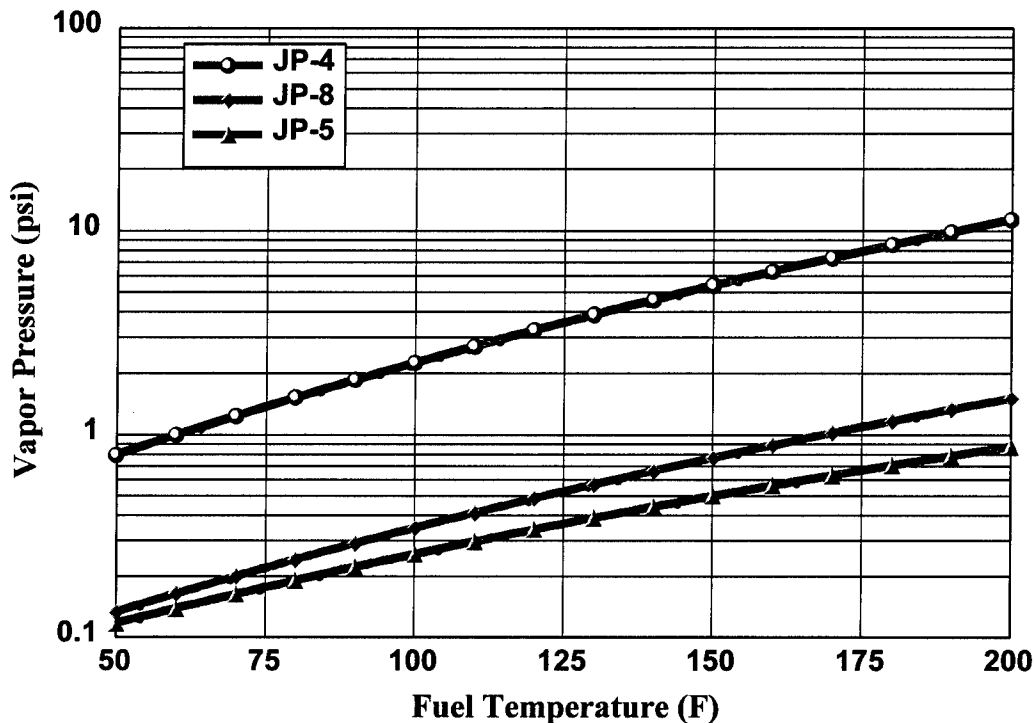
Graph 1

Average Spark Ignition Heights Above a 1'X1' Fuel Spill



Graph 2

Peak Spark Ignition Heights Above a 1'X1' Fuel Spill



Graph 3

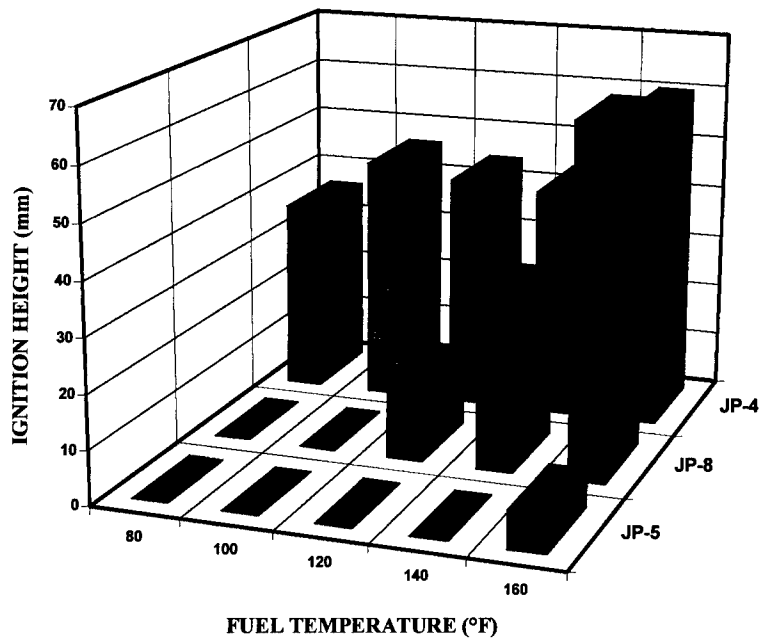
Fuel Vapor Pressures²

The fuel vapor ignitions occurred less than three inches above the fuel spill in all of the tests (see also Graphs 4 and 5). When scaled up based on Eggleston and Pish¹, the threat from fuel vapor ignition would be less than six inches in a hangar for JP-8 fuel temperatures of 130°-160°F and no threat for fuel temperatures below 100°F. Dilution of the flammable vapors due to convection currents could be expected to happen for a fuel spill in a hangar. If this happens, the flammable vapor threat should be considered equivalent to the peak ignition values.

Flame Ignition Tests

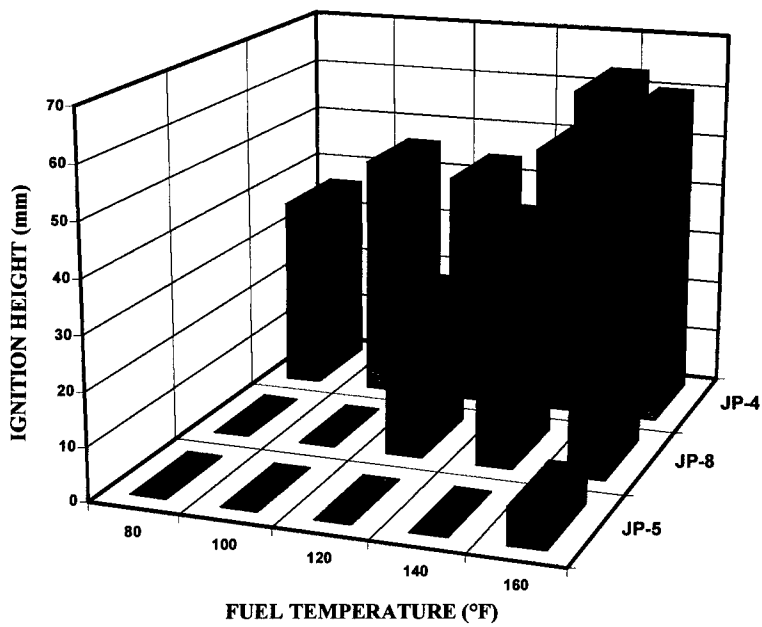
Flame ignition tests of JP-4, JP-8 and JP-5 were conducted similar to spark ignition tests. Ten tests of each fuel were conducted between 80° and 170°F. The results were used to calculate averages for each fuel which are plotted in Graph 4. The most noticeable result of this test was that ignition heights were higher than that for the spark ignition source tests. Although both of these items were high-energy ignition sources, the flame had more surface area which increased the possibility of reacting with flammable vapors.

As with the spark ignition tests, the peak ignition heights should be considered when evaluating the ignition threat. Peak values for flame ignition are shown in Graph 5. JP-8 ignition height at 130°-140°F appears to approach the ignition height of JP-4 at 80°F. Therefore the threat of ignition of JP-8 at 30°F above its flash point from a flame or electrical arc in a hangar should be expected to equal that of JP-4 at 80°F. Ignition of JP-8 fuel vapors at temperatures below 100°F will not occur without some heating of the fuel.



Graph 4

Average Propane Flame Ignition Heights Above a 1'X1' Fuel Spill



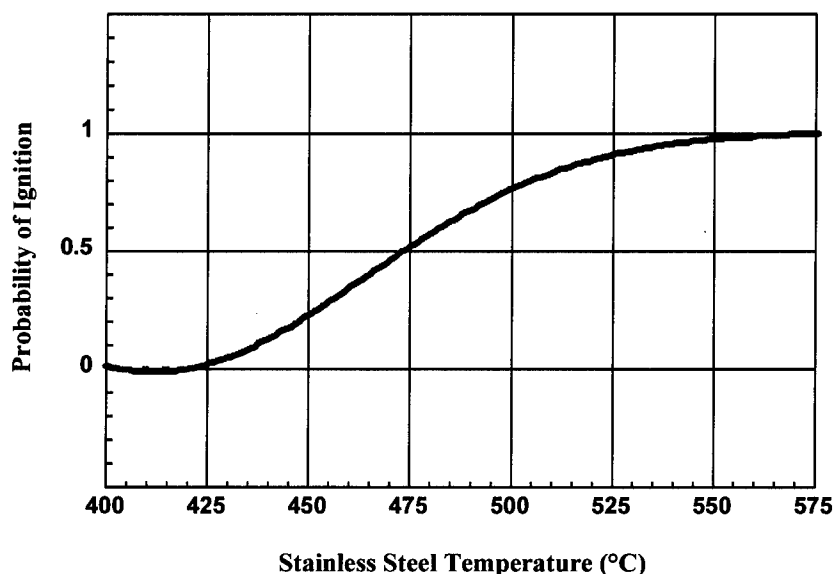
Graph 5

Peak Propane Flame Ignition Heights Above a 1'X1' Fuel Spill

Hot Surface Ignition

Fuel ignition as a result of contact with a hot surface was evaluated in the analytical chemistry facility. JP-4, JP-8 and JP-5 fuels were tested for ignition on a hot stainless steel surface. The results of the tests showed that the fuels did not ignite on contact below a certain temperature and they ignited consistently above certain temperatures. There was a range of temperatures in-between where ignition and no ignition of the fuel resulted.

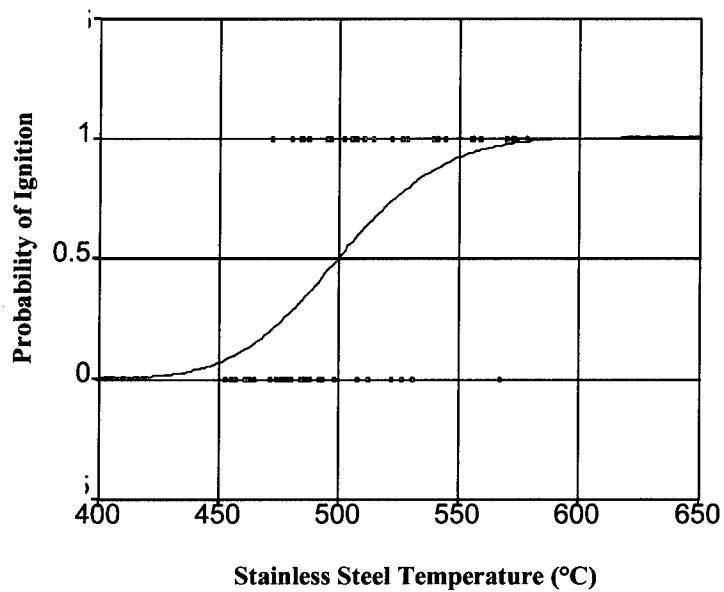
JP-4, JP-8, and JP-5 all have similar ignition properties on hot surfaces. Graphs 6-8 show hot stainless steel surface, fuel ignition test results. The points on the graph represent data collected in the laboratory. A point on line zero (0) indicates a temperature where the fuel did not ignite and a point on line one (1) denotes fuel ignition. The curve plotted on the graph is the probability that the fuel will ignite at that temperature. This is an estimate based on test results. Graph 6 includes data for JP-8. JP-8 ignited in every test when surface temperatures were above 1000°F (536°C) and did not ignite when temperatures were below 815°F (435°C). JP-4, in Graph 7, ignited in every test when surface temperatures were above 1050°F (565°C) and did not ignite when temperatures were below 885°F (474°C). JP-5 results are in Graph 8. JP-5 ignited in every test when surface temperatures were above 965°F (518°C) and did not ignite when temperatures were below 900°F (482°C). Hot surface ignition is virtually the same for the three fuels.



Graph 6: JP-8 Fuel Probability of Hot Stainless Steel Surface Ignition

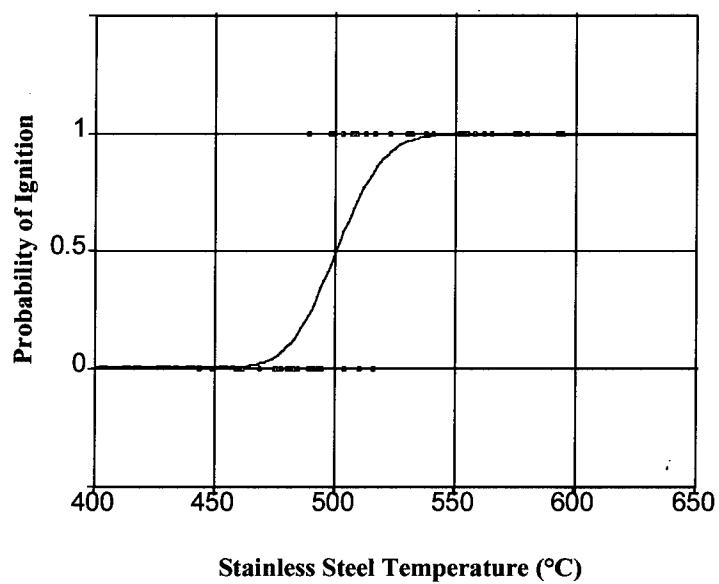
Field Ignition Tests

JP-4 and JP-8 were evaluated at Test Range I and Test Range II for ignition characteristics when exposed to hazardous electrical tools and equipment, welding and acetylene cutting operations, electrical arcs and ignited matches. The test setup and results are located in Appendix I.



Graph 7

JP-4 Fuel Probability of Hot Stainless Steel Surface Ignition

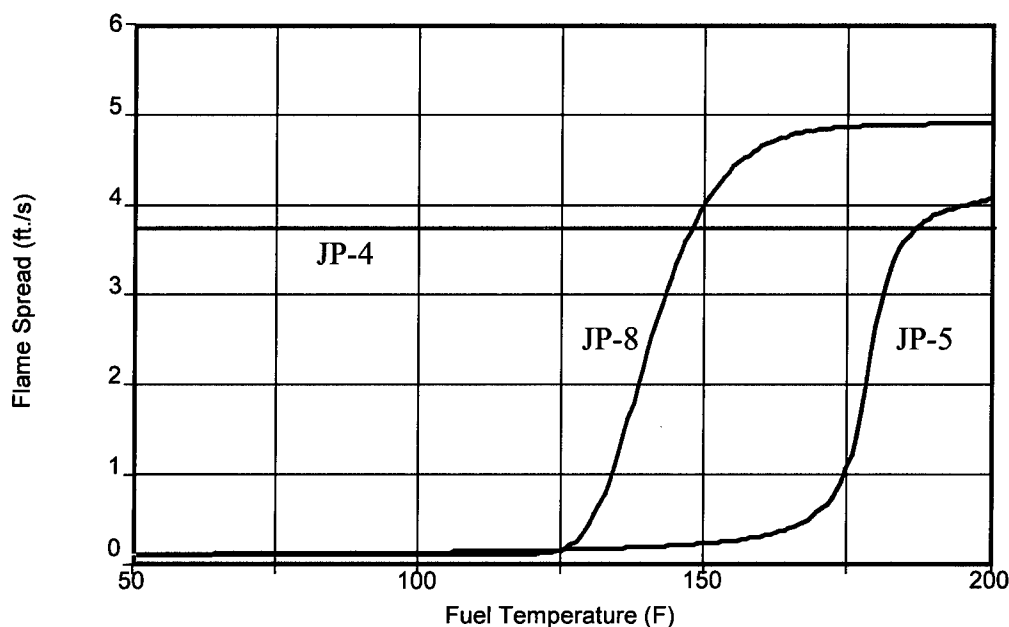


Graph 8

JP-5 Fuel Probability of Hot Stainless Steel Surface Ignition

B. FLAME SPREAD

Flame spread rates were measured in the analytical chemistry facility for fuels ranging in temperature from 80°F to 200°F. Graph 9 shows the measured flame spread rate for JP-4, JP-8 and JP-5 as a function of temperature. The flame spread rate of JP-8 and JP-5 is less than 0.3 feet per second (fps) when the fuel's temperature is below its flash point. These spread rates increase with temperature as the fuels emit more vapors due to increasing vapor pressures. Reliability of these propagation rates is ± 0.2 fps based on data acquisition rate and thermocouple position measurement.



Graph 9

Fuel Flame Spread Rates

It is known that below a fuel's flash point the flame spread rate is not a constant as it would appear from Graph 9. The flame spread rate increases during fire growth as radiation from the fire causes a rise in the temperature and volatility of the fuel ahead of the flame front. Images taken from video tape in Figures 6-11 illustrate this point (Note: The dark background in the images are caused by the video recorders automatic light adjustment). JP-4 at 92°F is well above its flash point of 0°F for the test shown in Figures 6-8. The flame spread rate of 5.7 fps (Each grid on the concrete surface is 1 square foot) is constant across the fuel spill. JP-8, tested at 90°F (flash point 110°F), takes 36 seconds, as shown in Figure 10 to travel the same distance that JP-4 traveled in one second. However, as the fire continues to grow, as shown in Figure 11, JP-8 takes only 13 seconds to travel the same distance (5.7 feet). It is obvious that as the flame height increases, more energy is radiated to the fuel increasing its temperature and flame spread rate.

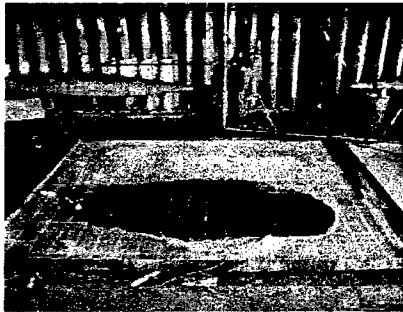


Figure 6
JP-4 Ignition

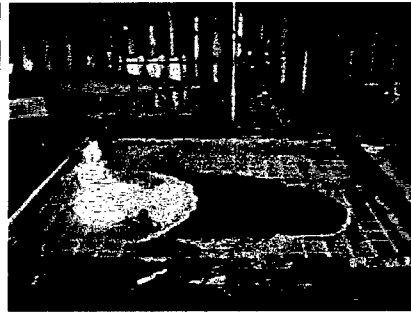


Figure 7
JP-4, One (1) Second after Ignition

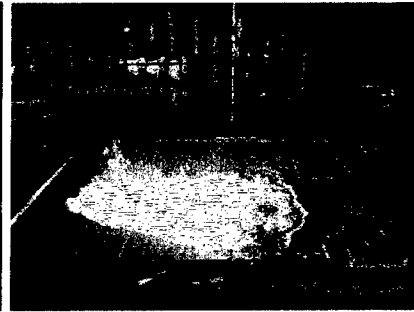


Figure 8
JP-4, Two (2) Seconds after Ignition

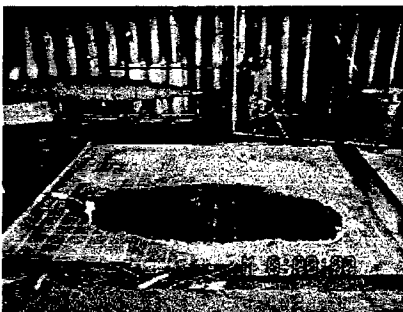


Figure 9
JP-8 Ignition

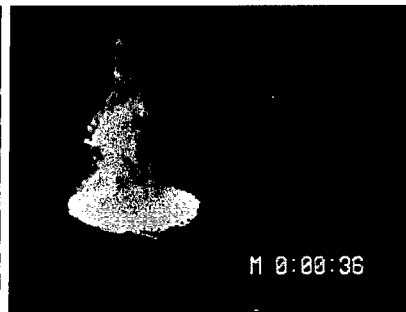


Figure 10
JP-8, 36 Seconds after Ignition

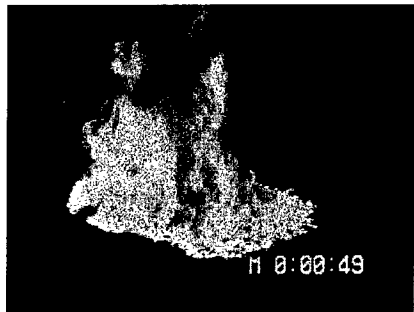


Figure 11
JP-8, 49 Seconds after Ignition

The flame spread rate of JP-4 should be constant when it is well above its flash point. Tests in this study showed a flame spread rate of 5.7 fps. Other publications have reported this rate to be 10 fps or higher. In this test we recorded the flame spread in one direction (or radially). If the fuel had been ignited in the middle of the spill, the flames would have traveled 5.7 feet per second in all directions, and the flames would have spread across the entire spill in about 1.3 seconds. Calculating the flame spread from this data would effectively double the radial flame spread and provide similar results to the 10 fps mentioned above.

C. HOT FUEL SPILL THREAT

It has been shown that JP-8 at 110°F or above is volatile and its vapors can be ignited. JP-8 at 140°F is very much like JP-4 at room temperature (i.e. easy to light with fast flame spread). For fuel spills it is important to know the threat zones associated with different fuel flow rates and sizes. A computational fluid dynamics (CFD) model was developed to predict fuel spill temperatures. The model predicts what happens radially from a hot fuel spill on a flat concrete surface and shows where fuel temperatures exist above the flash point of JP-8.

This is a two-dimensional, time-dependent problem. Temperature, T , will certainly depend on the distance, r , from the center of the spill, decreasing T as r increases. T will also decrease with the increasing distance below the surface, z . As you get deeper in the fuel, T should drop. Upon entering the concrete, T should decrease quickly. The CFD model is used to investigate the temperature distribution of the hot fuel as it spreads out radially over the cool concrete.

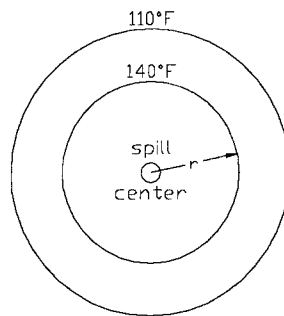


Figure 12
Fuel Spill Temperature Distribution

The model was first validated by comparing results with actual tests performed at Test Range II. The CFD model made it easy to vary fuel spill parameters and quickly view the results without the time, safety, and environmental concerns associated with physical testing. It should be noted that the CFD model did not take into account losses of heat to the air. Although the thermal conductivity of air is relatively small, so that air makes a good insulator, the insulating efficiency of a large amount of air - as found over a fuel spill - is reduced because of convection. As soon as there is a significant temperature difference between different parts of the airspace, convection currents act to equalize the temperature - like a wind blowing over the fuel - and the effective conductivity is increased, drawing heat out of the fuel. The model of the 160°F fuel spills predict only a slightly higher fuel temperature distribution as compared to our experimental results. Further evolution of the model is needed for fuel temperatures above 160°F. Also the CFD model only predicted temperatures out to a radial distance of 5ft. To compute threat zones associated with high fuel temperatures and flow rates the model should be extended.

There are many parameters that effect the temperature distribution of a fuel spill across the surface of a concrete floor. These are: initial fuel temperature, flow rate, time since flow began, ambient conditions, fuel layer thickness, and even concrete properties. The first three being far more important than the others. As the hot fuel hits the cool concrete, heat from the fuel is transferred to the concrete, heating up the concrete. Figure 13 shows a view of the temperature distribution into concrete from a one GPM, 160°F JP-8 fuel spill, five minutes after the spill begins. This heat transfer rate depends on the above mentioned properties. As the heat builds up a thermal layer in the concrete over time, there is nowhere for the heat in the fuel to go, so the hot fuel travels radially outward losing speed and transferring heat to cooler sections of concrete. One would therefore expect to see higher fuel temperatures toward the center of the spill, increasing with time, and higher temperatures at higher fuel flow rates over the same period of time.

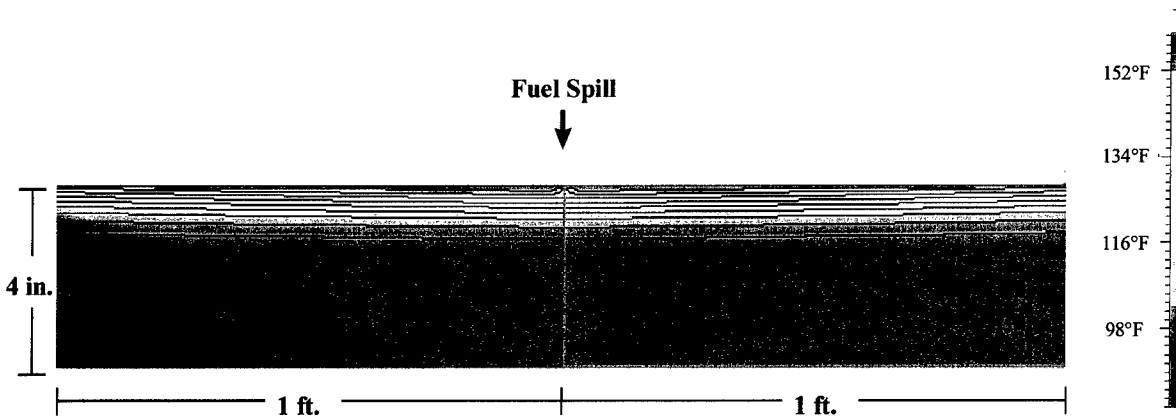
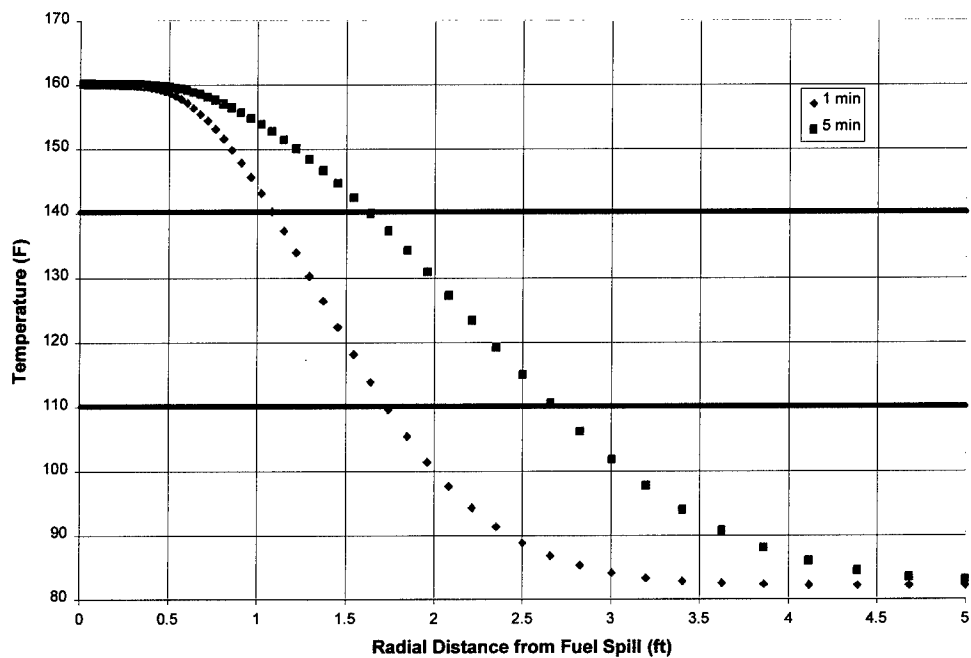


Figure 13
One-Foot Radial Temperature Distribution into Concrete

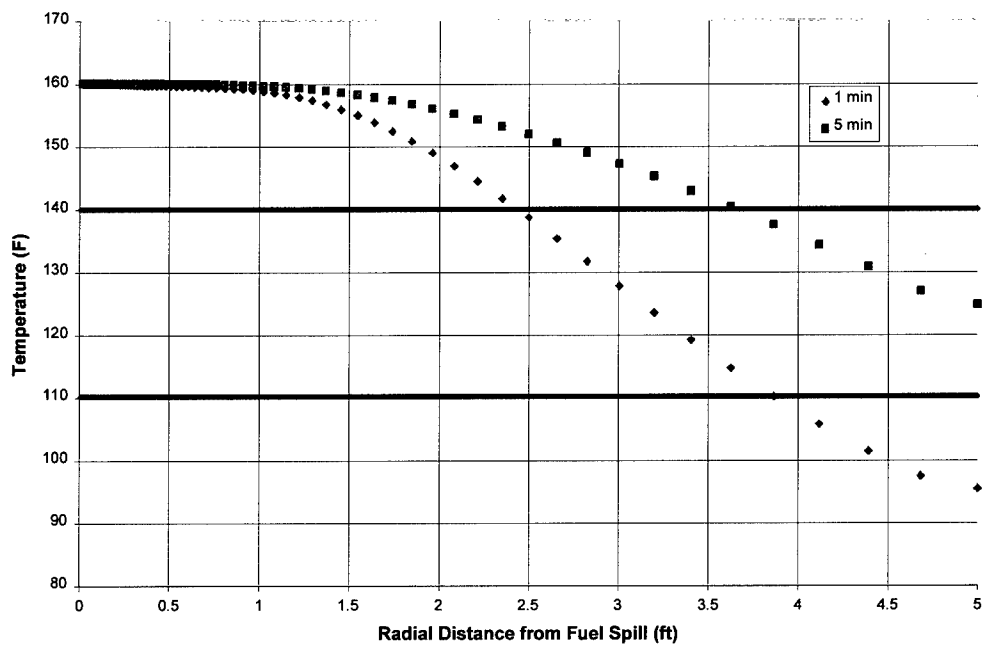
Graphs 10 and 11 show results from the CFD model. Fuel spill flow rates of one GPM and five GPM and fuel temperatures of 120°F and 160°F were chosen to demonstrate CFD model predictions. The initial concrete temperature was 80°F for both demonstrations. Graph 10 predicts the temperature drop of a one GPM, 160°F fuel spill as it travels outward from the center of the spill. After one minute of fuel flow, the fuel temperature is 140°F 1.1 feet from the center of the spill and the temperature is 110°F (measured flash point of JP-8) at a radius of 1.7 feet. After five minutes, the JP-8 fuel is at or above its 110°F flash point over a radius of 2.7 feet. Graph 11 is a prediction of a five GPM, 160°F fuel spill. Fuel temperatures of 110°F extend out radially 3.9 feet one minute after the spill begins and extend greater than five feet for a five minute spill duration. Table 3 tabulates this data and similar data for a 120°F fuel spill.

Table 3
CFD Model - Hot Fuel Spill Predictions

Fuel Flow Rate (GPM)	Initial Fuel Temperature (°F)	Time From Fuel Flow Initiation (min.)	Radial Distance of 110°F Fuel (ft.)	Radial Distance of 140°F Fuel (ft.)
1	160°F	1	1.7	1.1
1	160°F	5	2.7	1.6
1	120°F	1	1.1	n/a
1	120°F	5	1.7	n/a
5	160°F	1	3.9	2.4
5	160°F	5	>5.0	3.7
5	120°F	1	2.5	n/a
5	120°F	5	3.6	n/a



Graph 10: One GPM JP-8 Spill



Graph 11: Five GPM JP-8 Spill

D. FIRE INTENSITY

This study evaluated JP-4, JP-8, and JP-5 flat-plate fuel spill fires for their fire intensity over time. Many studies have been conducted on pool fire energy release, however, the geometry of the pool fire tests are different than flat-plate tests. Pool fires are usually conducted inside of a steel pan with a deep layer of fuel that allows burn times greater than four minutes. Additionally, the fuel is floated on a layer of water inside the test pan. A more realistic hangar fire scenario is a flat-plate spill fire because these tests allow the fuel to seek an equilibrium depth on a concrete surface which in turn causes shorter burn times. Also, when burning, the fuel is in contact with a concrete surface rather than a layer of water.

Flat-plate fuel spill fire tests have drawbacks when compared to pool fire tests. The size of the fire base cannot be controlled or accurately recorded, and in our tests, the fuel burning rates could not be recorded on the six-ton concrete test pad. This creates a problem in precisely determining heat release. Also, fuel burning times are limited by the fuel spill depth, thus limiting data collection times.

Problems encountered in these tests include the following: 1) The fire plume location could not be exactly predicted since the spill was not confined. 2) As the fuel on the high spots of the concrete floor was consumed during the test, the fire plume would move to the effective center of the remaining fuel, so the plume location was not consistent throughout a single test. 3) The slow flame spread rate of JP-8 and JP-5 also affected the fire plume location in some tests as parts of the fuel spill burned out before the flames spread across the spill. 4) The fires never reached a steady-state burning condition, so the maximum intensity of the fire was dependent on spill depth.

Tests were conducted with two-gallon fuel spills and five-gallon fuel spills. The JP-8 and JP-5 two-gallon fuel spills spread out over an average floor area of 47 ft² for an average fuel depth of 1/15" (The fuel was deeper or shallower in some areas due to non-uniformity of the concrete surface). Five-gallon spills covered 88 ft² of floor area on average with a spill depth of 1/11".

The two-gallon fuel fires were all conducted the same way in an attempt to get repeatable results. The fuel was spilled at the same location on the concrete pad and out of the same orifice for each test. The fires were ignited at the south side of the fuel spill and the flames spread to the north side for all tests. This resulted in a fire plume movement from south to north during all two-gallon tests. This result was most prominent with the lower volatility fuels. The result of this plume movement is that the location of the temperature and flux measuring instruments were only in the fire plume for a portion of the tests. These times were determined from video review.

Tests 2.2 and 2.4 were comparable two-gallon fuel spill JP-8 evaluations with similar fuel spill shapes and fire burn times. Test number 2.4 shows the time for the flame to spread across the surface of the spill to be 34 seconds. During both tests the flame heights and widths continued to grow until 63 seconds after ignition. After this, the fuel began to burn out in high

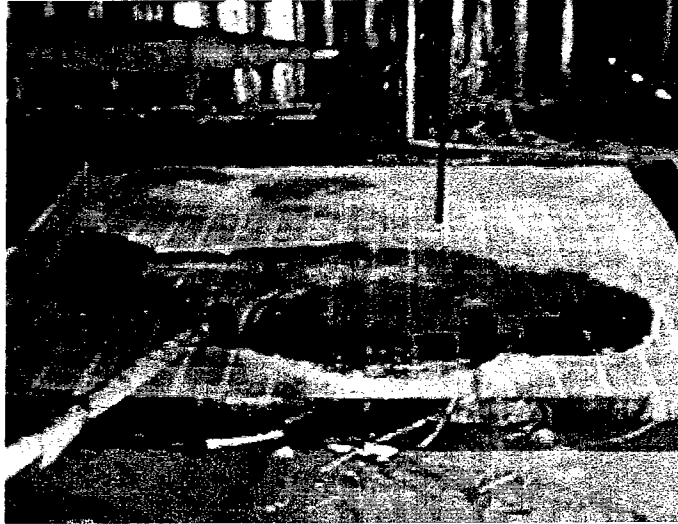


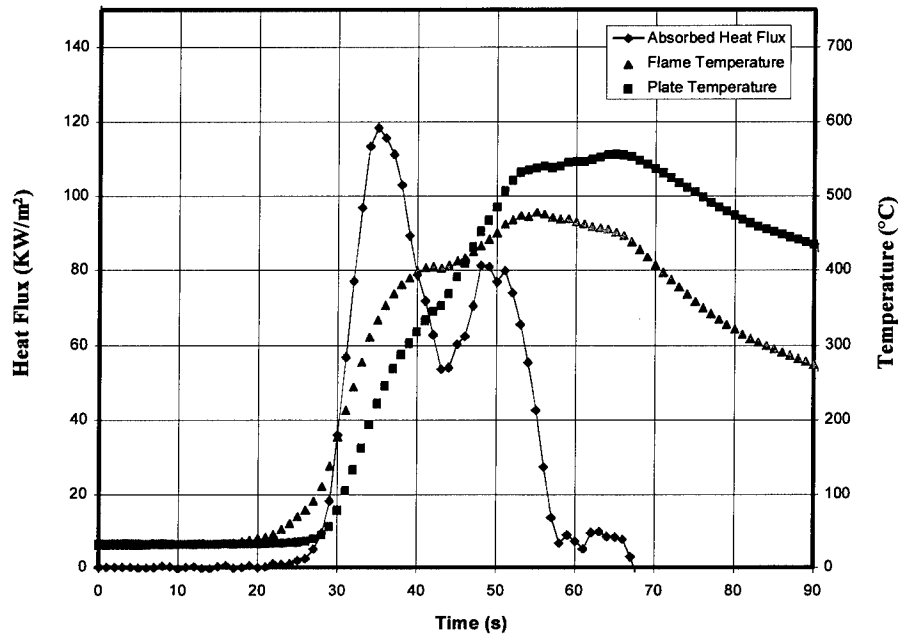
Figure 14
Five-Gallon JP-8 Fuel Spill (Facing East)

spots on the concrete pad, diminishing the fires. The fuel was exhausted in each test 100 seconds after ignition. The fires were in constant transition throughout the test, either growing or diminishing. Results of Test 2.4 are in Graph 12. Test 2.2 results are not plotted.

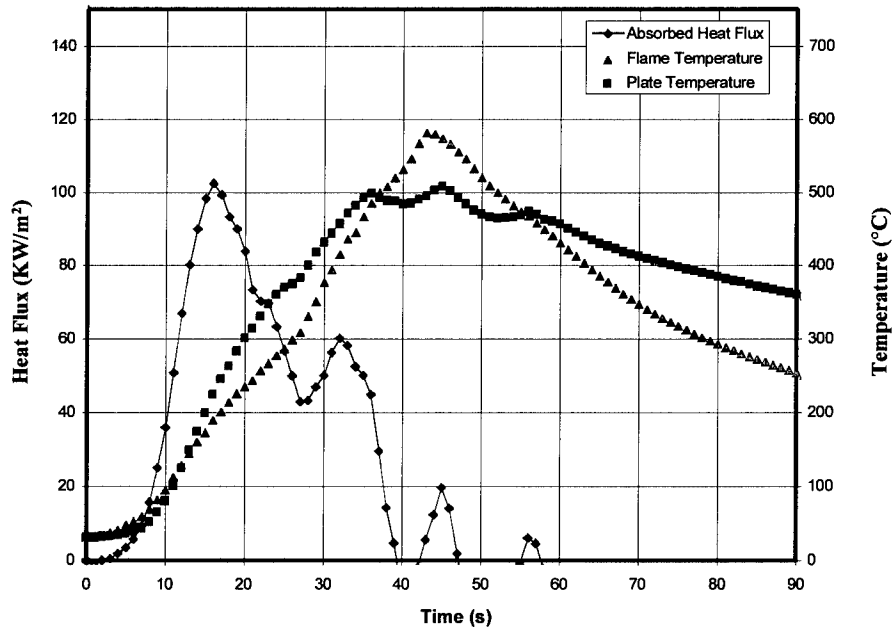
Likewise tests 2.5 and 2.7 were comparable JP-4 test fires. Results of Test 2.5 are in Graph 13. Flame spread across the JP-4 fuel spill was much faster as expected; it required approximately 1.5 seconds. Both fires had continuous flame heights above 15 feet within 10 seconds after ignition, and both fires began to diminish in size within 18 seconds after ignition. The fires had only small flames under two feet in height remaining 73 seconds after ignition.

Heat flux measurements were measured with DFT calorimeters above the fuel surface, therefore determining plume locations with respect to the sensors was important in comparing test results. The sensor located at 7.5 feet above the surface provided the best measurements for the two-gallon fuel spill tests. In Test 2.2 with JP-8 fuel, the DFT was closer to the center of the plume than in Test 2.4 or in the JP-4 two-gallon fires. The plume center was approximately 1.5 feet north of the sensor in Test 2.4. This matched the location of the plume for the JP-4 Tests 2.5 and 2.7. Graph 12 and 13 show the results of Tests 2.4 and 2.5, respectively, as temperatures and heat flux versus time. The temperatures and heat flux shown are values measured 1.5 feet from the fire plume center, 7.5 feet above the spill. Values measured in the center of the plume would be slightly higher.

Tests 2.8 and 2.9 with two-gallons of JP-5 fuel provided little data that was comparable with the two-gallon JP-4 and JP-8 fires. Flame spread time across the spill was 95 and 96 seconds for the two tests. Although the tests were exactly the same including the fuel spill and ignition location, the slow flame spread allowed the fuel on the south side of the spill to burn out before the north side of the spill was well developed. This resulted in the fire plume center three feet to the north of the DFT sensors.



Graph 12: Two-Gallon JP-8 Fire, Test 2.4 (Time 0 is ignition)
DFT plate and Thermocouple Located 7.5 Feet Above Fuel Surface



Graph 13: Two-Gallon JP-4 Fire, Test 2.5 (Time 0 is ignition)
DFT plate and Thermocouple Located 7.5 Feet Above Fuel Surface

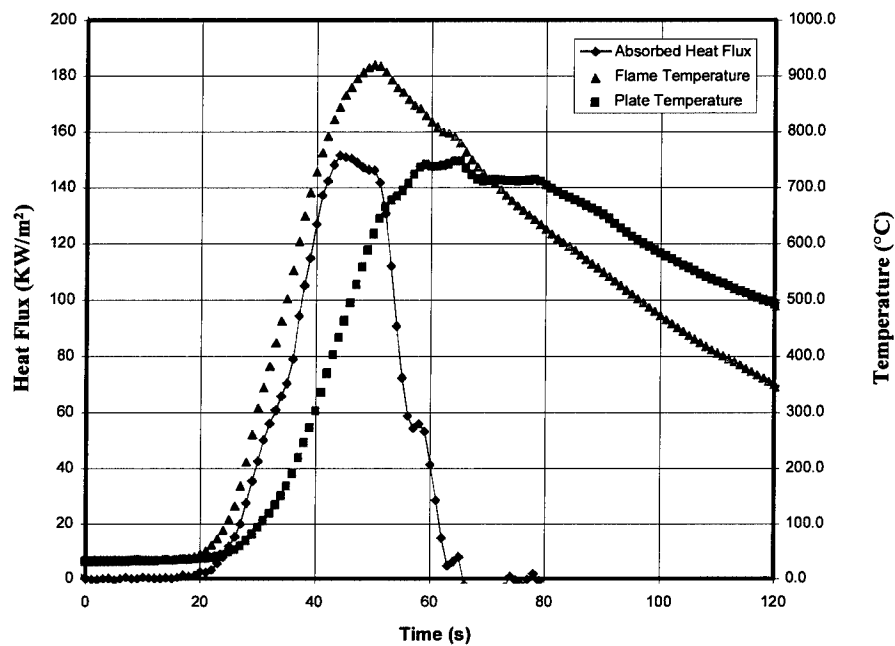
When the five-gallon, flat-plate fire tests were evaluated, a test with JP-4 and JP-8 (Tests 5.8 and 5.7 respectively) was conducted similar to the two-gallon tests except the spill was ignited on the north side of the spill. For all of the remaining five-gallon tests, the DFT sensors were positioned at heights of 3.8 and 7.5 feet to better capture plume intensities. A hot gas layer, created by the large fires in a 30-foot high facility, affected the upper fire plume in these tests, and plume wander affected the DFT located at 7.5 feet. In all five-gallon tests the bottom DFT sensor was recorded in the flame plume more often than the upper DFT. Therefore, it is the sensor discussed below. Tests 5.1-5.6 were ignited on the west side of the spill which balanced north-south flame spread and reduced the north-south plume movement seen in the two-gallon fuel spill fires. The reason for this was that the fuel spill areas were 1.5 times longer north-south than they were east-west.

Tests 5.3 and 5.6 are JP-8 five-gallon fuel spill fires. The average fuel depth on these spills was 0.09 inches. The time for flame spread across the spill was 47 and 38 seconds, respectively. In Test 5.3, the bottom DFT sensor was located 1.5 feet away from the fire plume center between 30 and 40 seconds after ignition. Data from this DFT sensor and a thermocouple mounted three inches from the north side of the sensor is shown in Graph 14. The fire plume moved from west to southeast during the test and enveloped the DFT from 41-58 seconds after ignition. The base of the fire began to diminish 54 seconds after ignition as the fuel around the edges was consumed. The fire burned at a somewhat steady rate from 30 until 82 seconds into the test, as apparent gains in the fire burning rate were offset by a decreasing fuel spill base. Both JP-8 fires burned out 120 seconds after ignition.

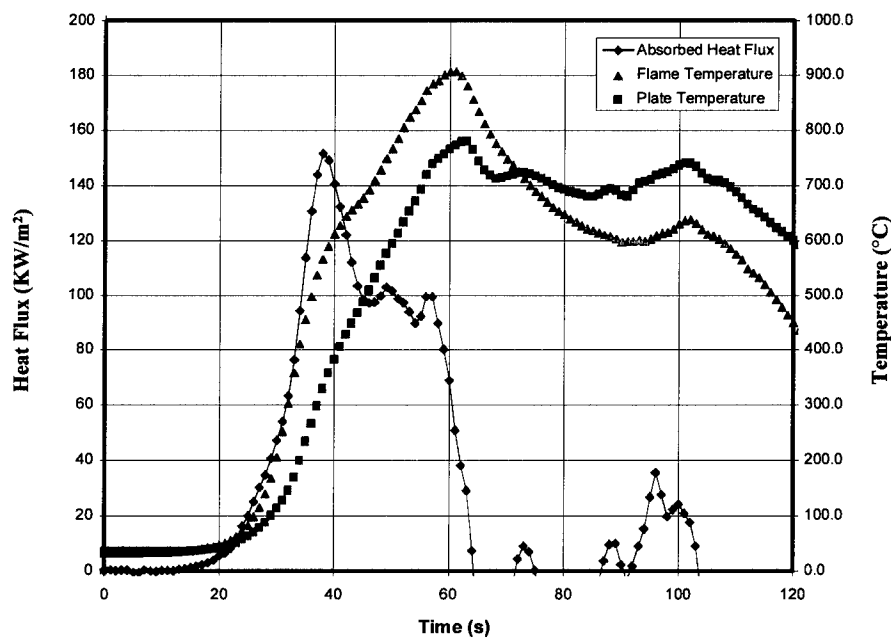
Test 5.6 was similar to Test 5.3. The DFT sensor at 3.8 feet above the spill was 1.5 feet from the center of the fire plume 33 seconds after ignition, and the plume moved to the sensor 60 seconds after ignition. The intensity of the fire began to drop rapidly 75 seconds into the fire. Data from this test is shown in Graph 15.

Tests 5.1 and 5.5 were the JP-4 fires plotted in Graphs 16 and 17, respectively. The DFT sensor at 3.8 feet was 1.5 feet from the center of the plume from 10-44 seconds and was in the center of the plume from 45- 90 seconds during Test 5.1. The two peaks on Graph 16 at 50 and 65 seconds are when the plume moved away from the sensors and then moved back over the sensors. In Test 5.5, Graph 17, the sensors were again 1.5 feet away from the plume centerline for the first 50 seconds of the fire and then the plume centerline moved to the sensor (Changes in plume position are caused by the shape of the fuel spill changing as the fuel is consumed by the fire). The flame intensity appeared to reach its maximum 34 seconds after ignition in Test 5.1 and 37 seconds after ignition in test 5.5. The flame intensity decreased for the remainder of the test as the fuel supply diminished. Both fires burned out 110 seconds after ignition. The smoke layer in the hangar came down below 10 feet by the end of both fires.

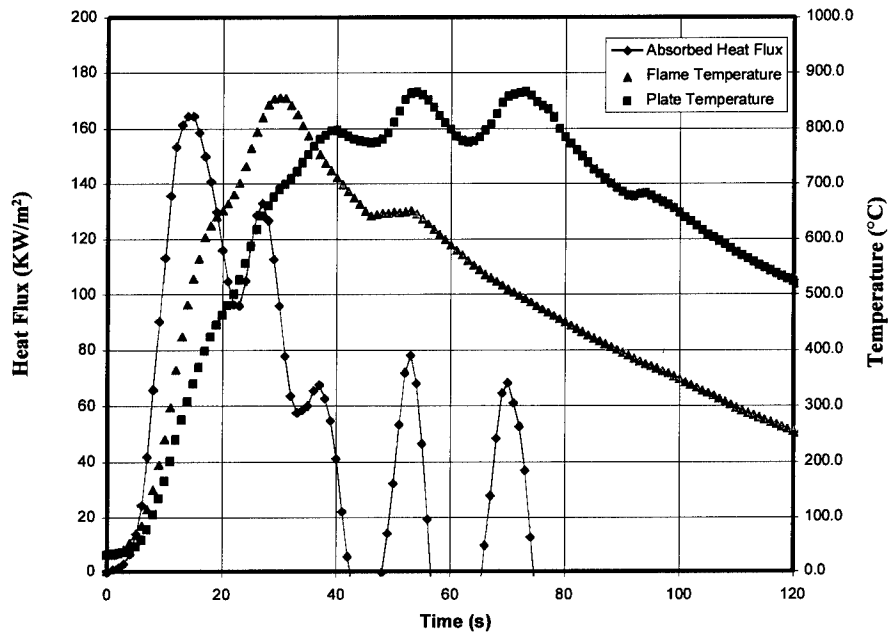
In Test 5.2, a JP-5 five-gallon fuel spill fire, the flames spread across the fuel spill in 97 seconds. Due to the slow flame spread rate, the base of the fire began to diminish where the fuel was ignited 95 seconds after ignition. Flame heights reached twelve feet 80 seconds after ignition, and the DFT and thermocouple sensors at 3.8 feet above the fuel spill were in the



Graph 14: Five-Gallon JP-8 Fire, Test 5.3 (Time 0 is ignition)
DFT plate and Thermocouple Located 3.8 Feet Above Fuel Surface

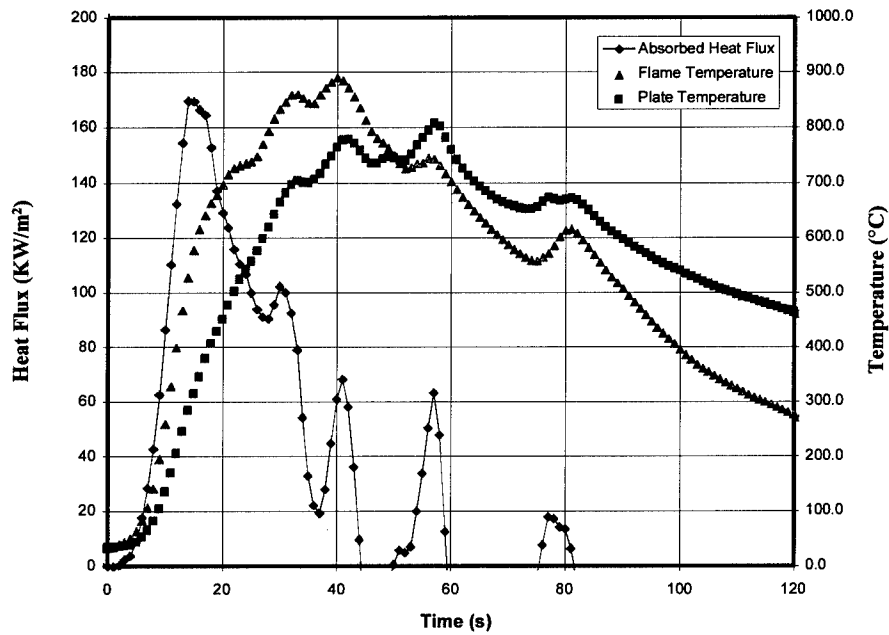


Graph 15: Five-Gallon JP-8 Fire, Test 5.6 (Time 0 is ignition)
DFT plate and Thermocouple Located 3.8 Feet Above Fuel Surface



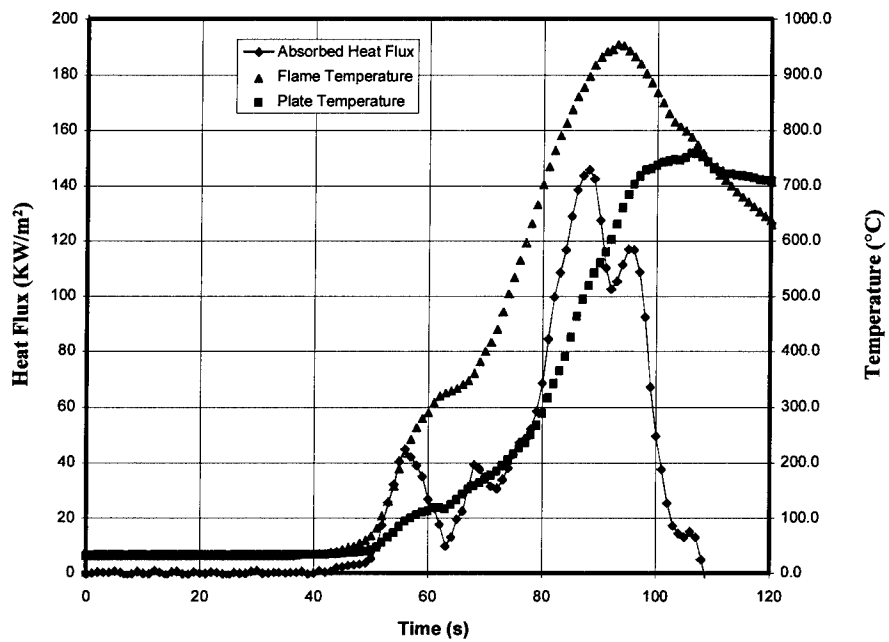
Graph 16: Five-Gallon JP-4 Fire, Test 5.1 (Time 0 is ignition)

DFT plate and Thermocouple Located 3.8 Feet Above Fuel Surface



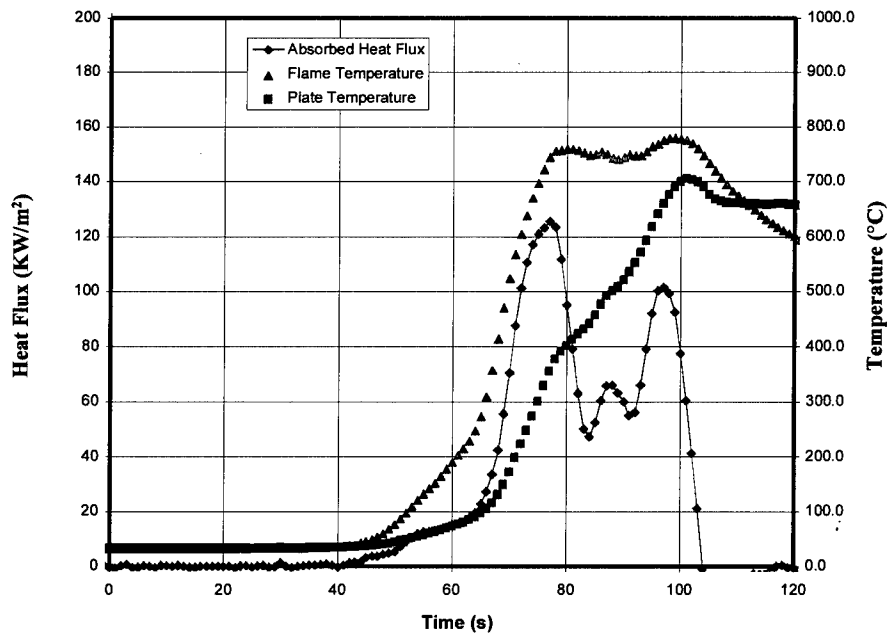
Graph 17: Five-Gallon JP-4 Fire, Test 5.5 (Time 0 is ignition)

DFT plate and Thermocouple Located 3.8 Feet Above Fuel Surface



Graph 18: Five-Gallon JP-5 Fire, Test 5.2 (Time 0 is ignition)

DFT plate and Thermocouple Located 3.8 Feet Above Fuel Surface



Graph 19: Five-Gallon JP-5 Fire, Test 5.4 (Time 0 is ignition)

DFT plate and Thermocouple Located 3.8 Feet Above Fuel Surface

flame plume from 80-95 seconds after ignition. From this point, the intensity of the fire slowly decreased as the base of the fire became smaller. This declining fire base caused a shift in the fire plume to the east, and the sensor was not in the fire plume 110 seconds after ignition.

The JP-5 fire, Test 5.4, developed more to the northwest side of the test pan and resulted in flames further away from the sensors than in other five-gallon tests. The center of the fire plume was 1.5 feet to the north of the sensors as the plume moved west to east during the test. The fire plume moved to the east of the sensors 95 seconds after ignition. This was 20 seconds earlier than in Test 5.2. Intensities are obviously lower in Graph 19 than in Graph 18 due to the distance of the fire plume from the sensors.

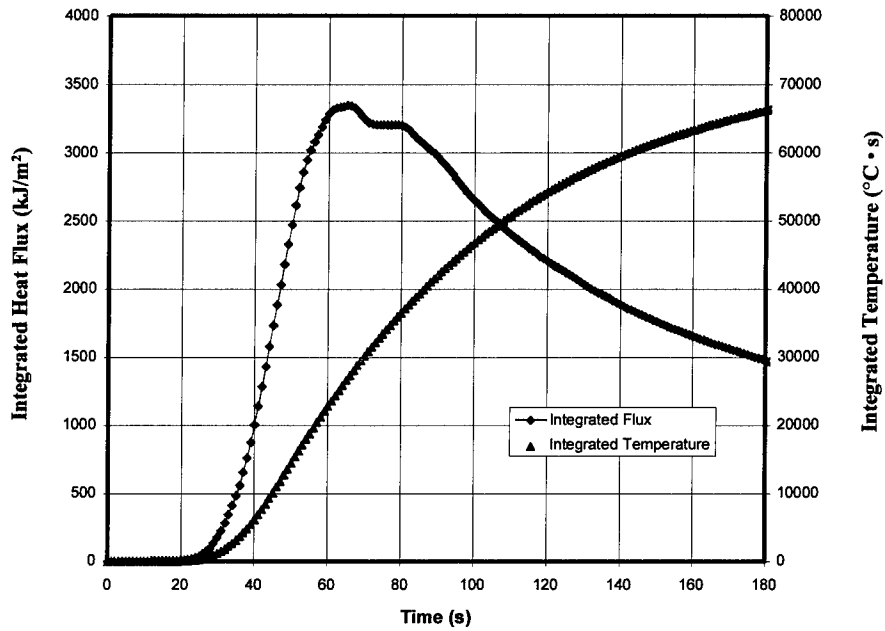
Table 4 summarizes the data from Tests 5.1-5.6. Peak heat fluxes and temperatures are shown with the time after ignition these peak values were achieved. Another method of evaluating these fires is to compare the duration of flame temperatures above a certain temperature. Based on a reported Duralumin critical skin damage temperature of 512°C³, a comparison temperature of 500°C was chosen.

Table 4
Heat Flux and Temperature Sensors Located 3.8 Feet Above the Fuel Spill

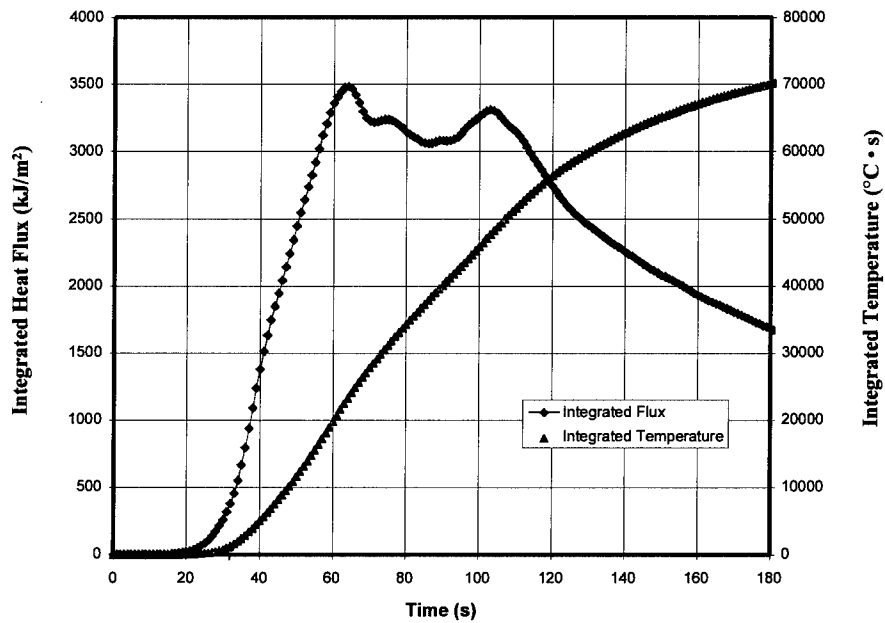
Test #	Fuel Type	Peak Heat Flux (kW/m ²)	Time From Ignition to Peak Heat Flux (s)	Peak Flame Temperature (°C)	Time From Ignition to Peak Temperature (s)	Sustained Flame Temperatures Above 500°C (s)
5.3	JP-8	152	44	921	50	62
5.6	JP-8	152	38	907	61	80
5.1	JP-4	164	14	856	30	57
5.5	JP-4	170	14	890	40	77
5.2	JP-5	146	88	955	93	69
5.4	JP-5	125	77	779	98	72

Graphs 20-25 show the integrated heat flux and integrated flame temperature for the sensor located at 3.8 feet above the fuel spill. These graphs present a different view of the data from Tests 5.1-5.6. Peak flux and temperature values for these tests are shown in Graphs 14-19. The integrated data is a better representation of the total exposure that an object in the flames will have throughout the entire fire. The point on the graphs where the integrated flux begins to decrease represents a decreasing plate temperature on the DFT sensor as the flames diminish or move away from the sensor.

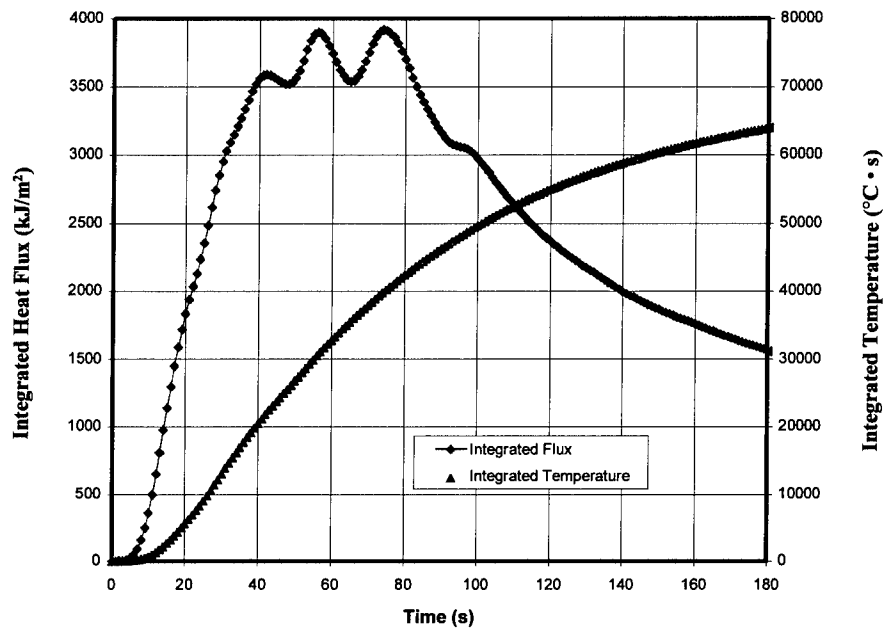
Heat flux sensors located outside of the test pan were positioned to measure heat transfer to an object outside of the fire. Two thin-skin calorimeter sensors were located 3.8 and 7.5 feet above the fuel spill and four feet south of the edge of the fuel spill. This placed the sensors approximately 11 feet from the center of the spill (see Figure 5). Graphs 26-28 show the response of the calorimeter located at 7.5 feet to JP-8 (Test 5.6), JP-4 (Test 5.5), and JP-5 (Test 5.4), respectively (Note: Graph 28 is plotted on a 180 second time scale).



Graph 20: Five-Gallon JP-8 Fire, Test 5.3 (Time 0 is ignition)
Integrated Heat Flux and Integrated Flame Temperature from Graph 14

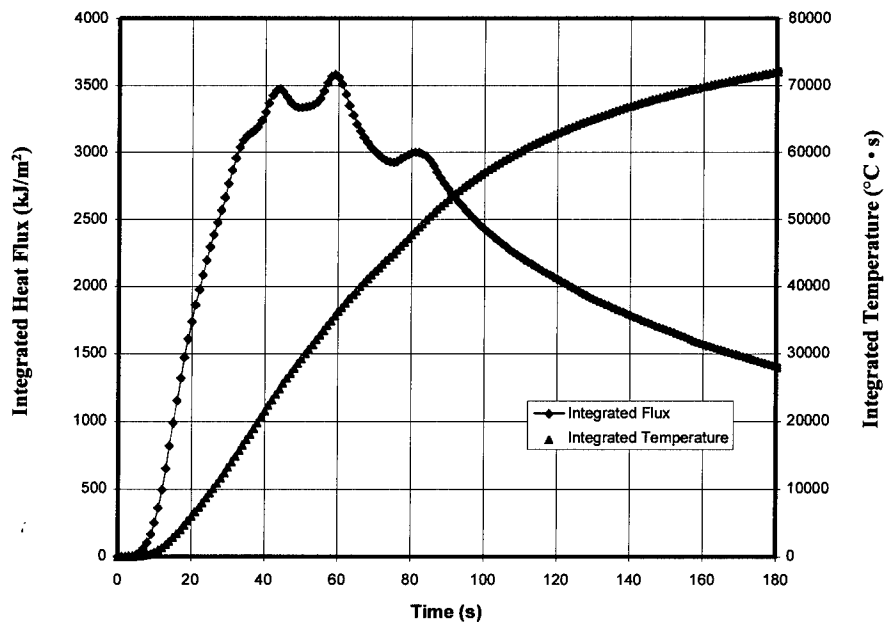


Graph 21: Five-Gallon JP-8 Fire, Test 5.6 (Time 0 is ignition)
Integrated Heat Flux and Integrated Flame Temperature from Graph 15



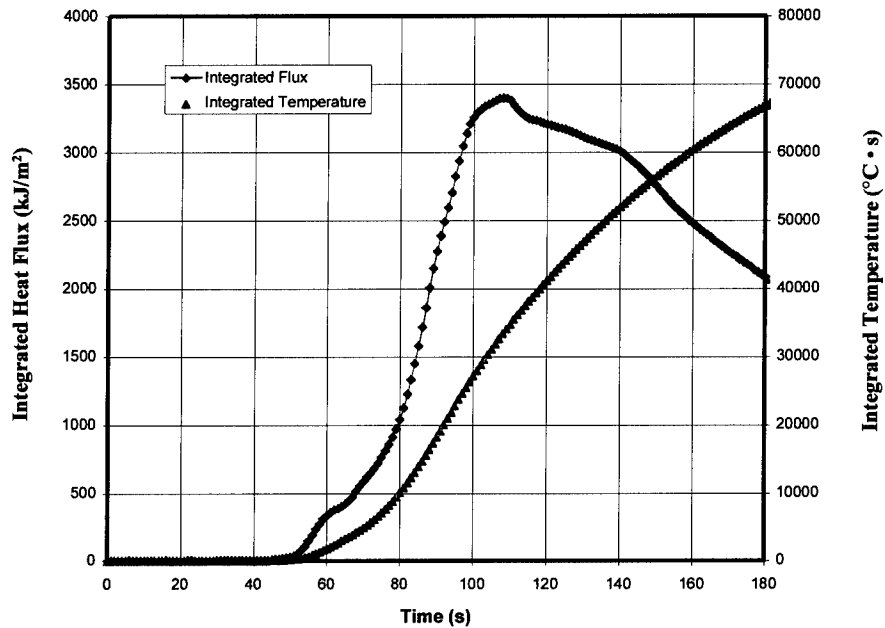
Graph 22 : Five-Gallon JP-4 Fire, Test 5.1 (Time 0 is ignition)

Integrated Heat Flux and Integrated Flame Temperature from Graph 16



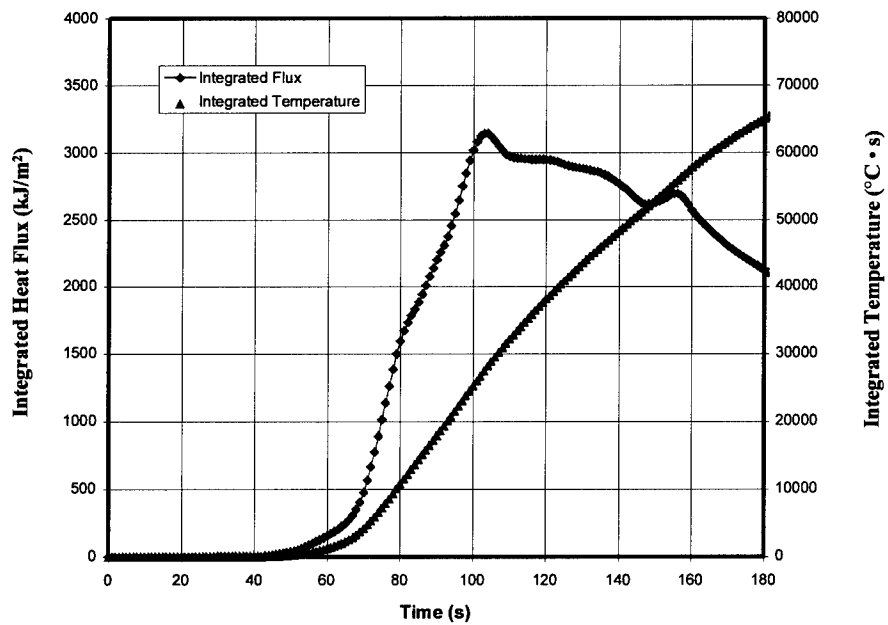
Graph 23 : Five-Gallon JP-4 Fire, Test 5.5 (Time 0 is ignition)

Integrated Heat Flux and Integrated Flame Temperature from Graph 17



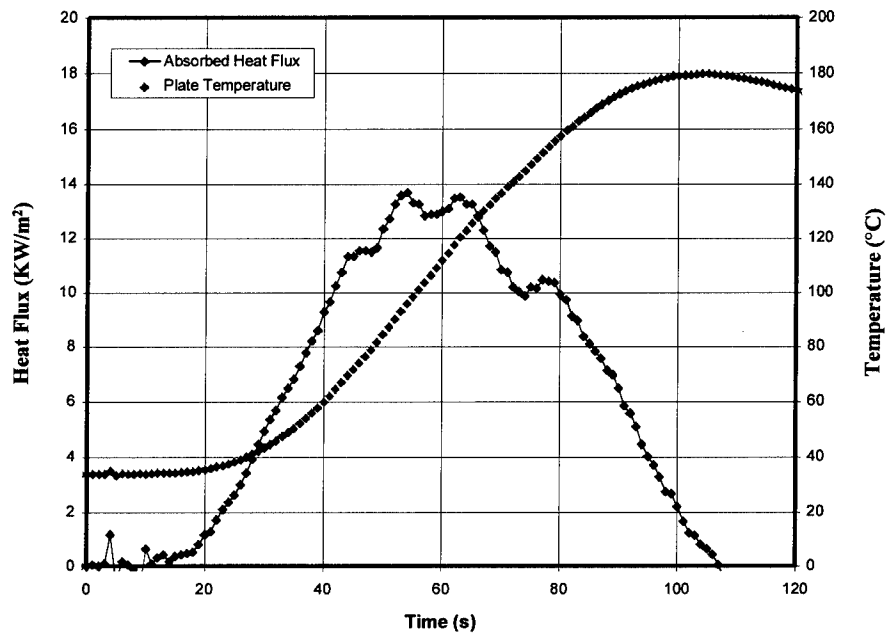
Graph 24 : Five-Gallon JP-5 Fire, Test 5.2 (Time 0 is ignition)

Integrated Heat Flux and Integrated Flame Temperature from Graph 18



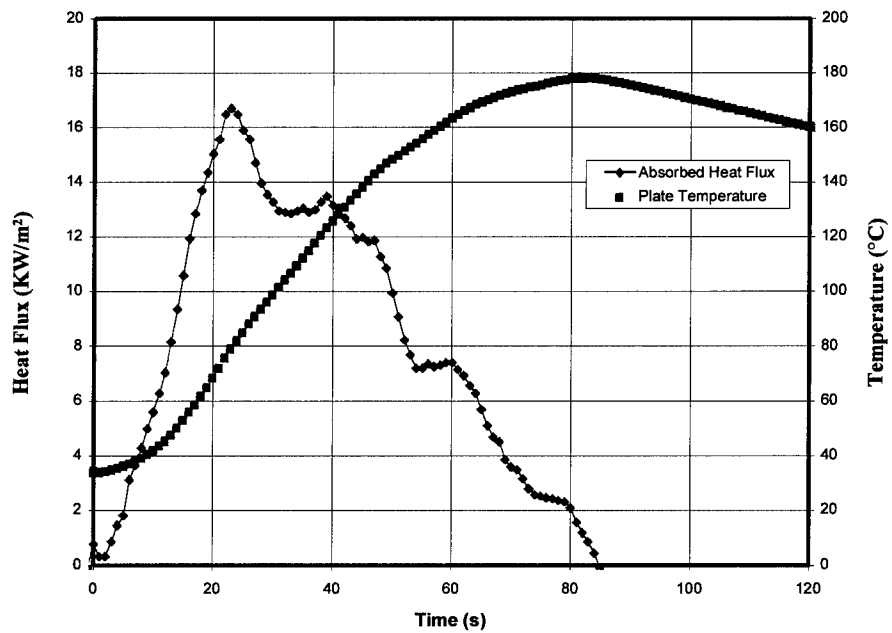
Graph 25 : Five-Gallon JP-5 Fire, Test 5.4 (Time 0 is ignition)

Integrated Heat Flux and Integrated Flame Temperature from Graph 19



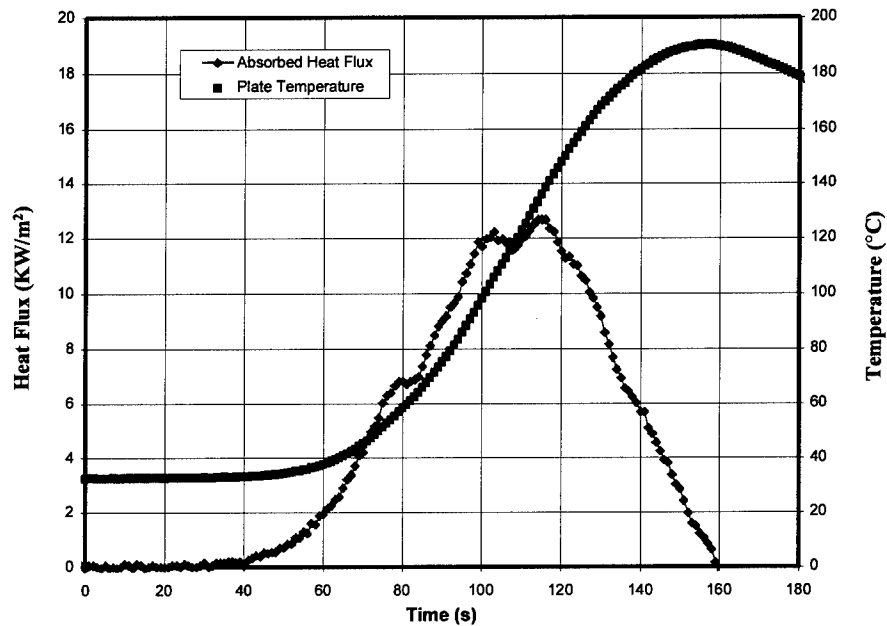
Graph 26: Five-Gallon JP-8 Fire, Test 5.6 (Time 0 is ignition)

Sensor Located 4 Feet from Fuel Spill & 7.5 Feet Above Fuel Surface



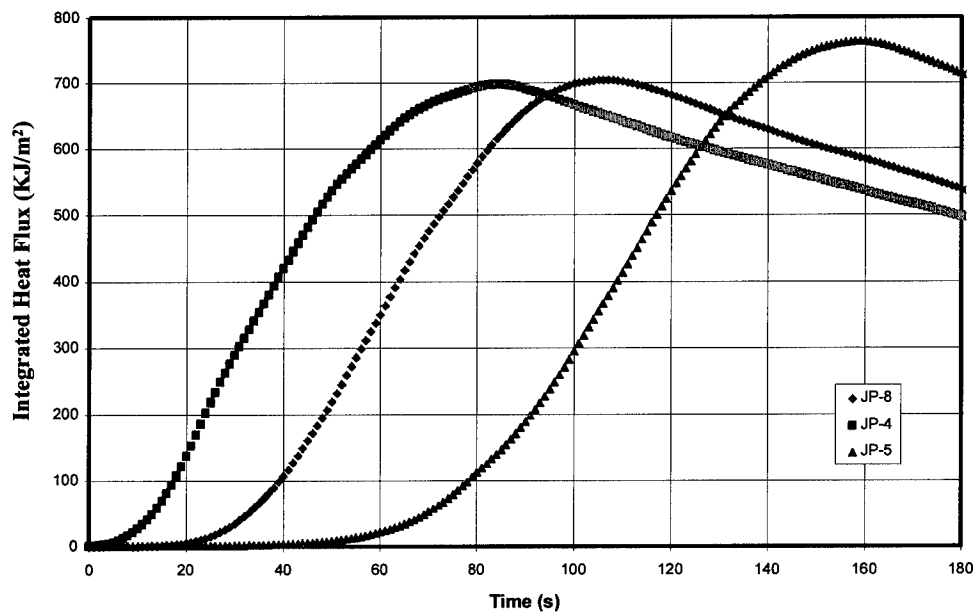
Graph 27: Five-Gallon JP-4 Fire, Test 5.5 (Time 0 is ignition)

Sensor Located 4 Feet from Fuel Spill & 7.5 Feet Above Fuel Surface



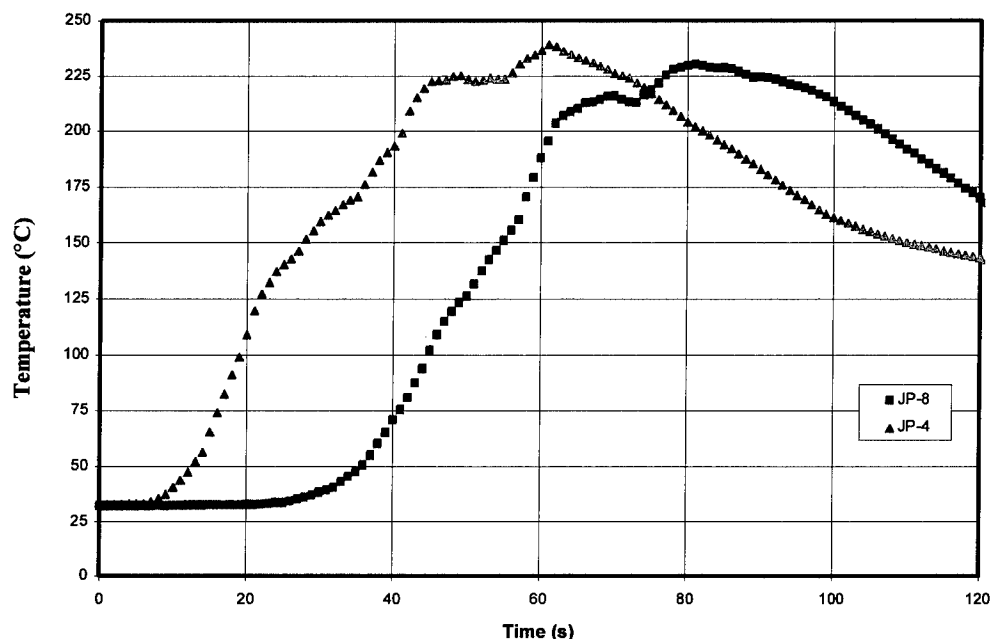
Graph 28: Five-Gallon JP-5 Fire, Test 5.4 (Time 0 is ignition)

Sensor Located 4 Feet from Fuel Spill & 7.5 Feet Above Fuel Surface



Graph 29: Five-Gallon JP Fires, Test #s 5.4, 5.5, & 5.6

Integrated Heat Fluxes Measured 4 Feet from Fuel Spill & 7.5 Feet Above Fuel Surface



Graph 30: Ceiling Temperature Tests 5.7 & 5.8 (Time 0 is Ignition)

Table 5
Integrated Heat Flux Values from Table 4

Test #	Fuel Type	Peak Integrated Heat Flux (kJ/m ²)	Time From Ignition to Peak Integrated Heat Flux (s)
5.3	JP-8	3349	65
5.6	JP-8	3483	64
5.1	JP-4	3588 (3917*)	42 (74*)
5.5	JP-4	3581	59
5.2	JP-5	3401	108
5.4	JP-5	3144	103

*2nd peak, caused by plume movement

Tests 5.7 and 5.8 were five-gallon fuel spill fires conducted with JP-8 and JP-4, respectively. These tests were conducted with the DFT sensors in the same location as in the two-gallon spill fires. The fuel spills were ignited on the North side of the spill and propagated to the south side. Graph 30 shows temperatures from the two tests measured 23 feet above the fuel surface. Again, this shows the difference in the flame spread rate and the similarities of the temperatures produced by the fuels.

From Graphs 14-19 and Table 4, some differences and similarities in the fuels stand out. Due to its high volatility and flame spread, JP-4 becomes an intense fire quicker than JP-8 and JP-5. The time for each fuel to reach a maximum intensity is directly related to the fuels flame

spread rate. The DFT shows similar absorbed fluxes and plate temperatures for JP-4, JP-8 and only slightly lower fluxes for the JP-5 fuels. The fire depicted in Graph 19 (Test 5.4) developed further away from the sensor locations than the fires in Graphs 14-18 producing lower intensity results, although as Graph 29 shows, the integrated heat flux outside of the pan for this test is similar to the JP-8 and JP-4 test. The intensity of the fuel fires does not seem to diminish from the higher volatility fuel to the lower volatility fuel.

Graphs 20-25 show the integrated heat flux and integrated temperatures from Graphs 14-19 (Tests 5.1-5.6). The integrated heat flux is a measure of the total exposure of the flame on an object over the duration of the fire. The results show that JP-4, JP-8 and JP-5 have similar total heat flux exposure to objects in the flame zone, with JP-4 having values 10%-15% higher than JP-8. The integrated flame temperature of the fuels, when compared between tests, shows matching results for Tests 5.1-5.6.

Graphs 26-28 show equal maximum plate temperatures for JP-8 and JP-4 of 355°F (180°C) and a slightly higher plate temperature for the JP-5 test of 374°F (190°C) measured outside of the test pan. Again, these graphs clearly show the effects of flame spread on the time for a fire to reach maximum intensity. The absorbed heat flux in these three tests was comparable for all three fuels with JP-4 having a slightly higher peak heat flux. Graph 29 is a combination of JP-4, JP-8, and JP-5 integrated heat flux for Tests 5.4-5.6. It shows that JP-5 had a slightly higher but similar peak integrated flux as JP-4 and JP-8 outside of the fire plume.

In conclusion, these tests found that once the fuel fires reach full intensity, the JP-4, JP-8 and JP-5 flat-plate fire intensities were equivalent. The difference in the fuels is primarily in the time it takes for the fires to reach peak intensities, or flame spread differences. These peak intensities and total exposure to an object in or around the flame are similar for the three fuels. Fire suppression tests of JP-4 fuel spill fires and JP-4 pool fires had been previously conducted by Factory Mutual⁴. They concluded that spill fires would result in smaller fire plumes than pool fires. This result concurs with the flat-plate fires of this study in which the fires fuel supply diminished while the fire intensity was still increasing.

Test number 2.1 produced an interesting result. A two-gallon JP-8 fuel spill was ignited with a propane torch on the west side of the spill. Figure 15 shows the fire growth 40 seconds after ignition. The fire did not continue to spread across the surface in this test. The spill was apparently ignited at a high spot on the concrete pad. The fire consumed the available fuel at that location before the flame could spread to the remaining fuel. Figure 16 shows the fuel spill when the flames died down. The flames continued to flicker, as in Figure 16, four minutes after ignition when the test was terminated.

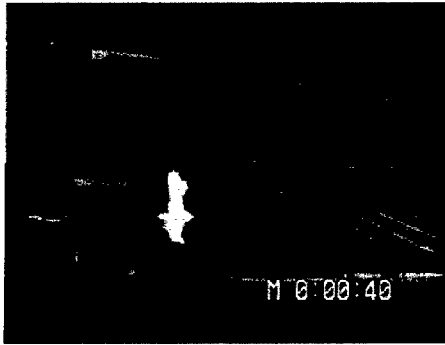


Figure 15
Test 2.1
40 Seconds After Ignition

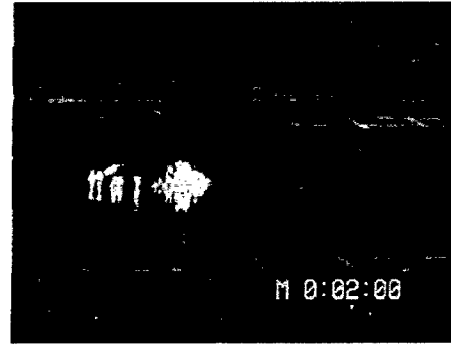


Figure 16
Test 2.1
120 Seconds After Ignition

SECTION IV

CONCLUSIONS AND RECOMMENDATIONS

The threat of a JP-8 fuel spill ignition in an Air Force hangar is greatly reduced when compared to the previous threat from JP-4 fuel. Under ambient hangar conditions (floor temperatures 60° - 90°F) an ambient JP-8 fuel spill produces insufficient vapors to support ignition. This is to say that JP-8 must be subjected to a sustained heat source in order to produce the vapors required for ignition. This makes the fuel safer from an ignition standpoint, and from a flame spread standpoint. An ambient JP-8 fuel spill can require a significant time (20-30 seconds) to build up the thermal flux necessary to increase the flame spread rate. While JP-4 grows to its full extent within a few seconds after ignition leaving a maintenance operator little time to respond, the JP-8 spill fire remains in its incipient stage 20-30 seconds after ignition allowing maintenance personnel time to react.

There is no prominent difference in the fire intensity of JP-4, JP-8 and JP-5 flat-plate fires once they reach full intensity. The main difference in the way the fuels burn is due to flame spread and fire growth rate. When the fuel fires achieve maximum intensity, heat flux and temperature measurements for the fuels are similar.

The inherent safety of JP-8, however, can cause individuals to become complacent in adhering to safety practices. NFPA 70, National Electric Code⁶, requires electrical connections, conduit, equipment, tools, heaters, and motors to comply with Class I Division II locations in Air Force hangars. Although JP-8 is a safer fuel than JP-4, safety practices, like those in the NFPA and OSHA guidelines, that can prevent possible fuel ignition sources should continue to be followed. Continuing fire safety education on the use of equipment and procedures for workers in Air Force hangars will result in a fire-safe environment.

A. CONCLUSIONS

1. JP-8 and JP-5 fuels do not produce sufficient vapors to support ignition at temperatures below their respective flash point. JP-8 and JP-5 must be subjected to a sustained high-energy heat source in order to produce the vapors required for ignition. When JP-8 or JP-5 are above their flash point, ignition of fuel vapors is possible. When the fuel temperatures are 30°F above their respective flash points, ignition properties are similar to JP-4 at 80°F.
2. The flame spread rate for JP-4 is 20 times greater than that of JP-8 when the fuel temperatures are below the flash point of JP-8 (100°F) and above the flash point of JP-4 (0°F). This is also true of the flame spread relationship between JP-4 and JP-5 (140°F).
3. In large fuel spill fires, flames radiate heat to the fuel in front of the flame front, increasing the fuel temperature. This heated fuel has a higher flame spread rate. JP-8 and JP-5 flame spread rate increases with increasing fuel temperature above their respective flash points.

4. Flame spread rate determines how long after fuel ignition that a JP-fuel fire becomes hazardous to adjacent equipment and structures. The difference in flame spread rate allows more time for personnel, a suppression system, or for the fire department to respond to a JP-8 or JP-5 fire.
5. Fuel spill data from these evaluations and from previous studies¹ indicate that fuel spill depths on flat concrete floors will not reach a depth of 1/8" except in the case of a low spot on the floor, equipment causing a damming effect of the fuel spill, or a high flow rate fuel spill which would have a short-term deeper spill depth.
6. There is no prominent difference in the fire intensity of JP-4, JP-8 and JP-5. The main difference in the way the fuels burn is due to flame spread and fire growth rate. When the fuel fires achieve maximum intensity, heat flux and temperature measurements for the fuels are similar.

B. RECOMMENDATIONS

1. Even though it has been determined that JP-8 provides greater fire safety than JP-4, it is prudent to determine the most cost effective intervention method should an inadvertent or accidental fire occur.
2. Reinforce the importance of complying with safety procedures (i.e. NFPA and OSHA) in hangars by requiring continuing fire safety education on the use of equipment and procedures for workers in Air Force hangars.

SECTION V

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APPENDIX I

IGNITION CHARACTERISTICS

Fuel ignition tests were conducted to determine the differences and similarities of JP-4 and JP-8 fuel spills when exposed to ignition sources that are common in everyday life. The fuels were exposed to the following: acetylene cutting, arc welding, disc grinder, bench grinder, 10,000V Arc, kitchen match, cigarette, electric drill, cordless drill, electric Dremil, 1500W electric space heater, trouble light, 110V electric pump motor, 500W halogen lamp, electric exhaust fan motor. Most of these objects and operations are not allowed in an aircraft hangar, however, they represent a wide variety of ignition sources. Results are summarized in Tables 1-1, 1-2, and 1-3.



Figure 1 - 1

Acetylene cutting and arc welding (Figure 1-1) operations were conducted at Test Range II. Three tests were conducted with each fuel. A steel plate was positioned two feet above the concrete floor. One-half gallon of fuel was spilled onto the floor below the edge of the steel plate. Fuel temperature was 84°-87°F for all tests. One minute after the fuel was spilled, welding and cutting operations commenced above the fuel spill. JP-4 ignited within two seconds after the operations begin in each test. Hot metal sparks from these operations contained the energy needed to ignite the flammable

vapor above the fuel spill. JP-8 fuel ignited in each test. Ignition happened 13-22 seconds after welding operations began and 19-68 seconds after acetylene cutting began. In each case sufficient energy from the hot metal particles were required to vaporize the JP-8 fuel to a point that a flammable vapor mixture was formed. The hot metal sparks then provided the energy needed for ignition of the vapors.


















Metal grinding operations were conducted with a handheld grinder. Fuel temperatures were 84°-86°F for all grinding tests. Handheld grinder operations were conducted on the steel plate in Figure 1-1. One-half gallon of fuel was spilled onto the floor and the grinding began one minute later. Sparks from the grinding were directed toward the fuel. JP-4 fuel ignited between 13-17 seconds in three tests. There was not enough energy transferred to the JP-8 fuel from the small metal sparks to produce ignitable vapors, and the fuel did not ignite in any of the three tests after two minutes.

The 10,000V spark plug used for ignition tests in the analytical chemistry facility was also used at Test Range II to evaluate fuel ignition. Although this spark plug is not a common item, it represents an electrical arc which can result from any use of AC or DC electrical power. The spark plug was tested above a fuel spill and was tested directly in the stream of flowing fuel. The spark plug was positioned four feet away from where one gallon of 83°-84°F fuel was spilled onto the concrete pad. The spark plug was one inch above the fuel and turned on when the fuel was spilled. JP-4 fuel ignited in two tests when the edge of the fuel spill passed underneath the electric arc. The test was conducted again with the ignitor three inches above the

floor and the fuel did not ignite. After the JP-4 fuel spills were complete, the spark plug was passed over the spill twice at three inches above the floor and the fuel did not ignite. JP-8 did not ignite with the spark plug one inch above the spill. JP-8 was not expected to ignite since it was below its flash point. After the JP-8 fuel spills were complete, the spark plug was passed over the spill twice at one inch above the floor and the fuel did not ignite. Since there was no ignition of the JP-8 fuel spill one inch above the floor, fuel ignition was not tested above this point.

The spark plug was then positioned one-inch off the floor, directly below a fuel discharge nozzle. The nozzle was located five feet above the floor. Fuel was spilled at one GPM onto the electrical arc. JP-8 and JP-4 both ignited within 10 seconds after the fuel spill started. JP-8 was ignited in this test since the spark plug became hot and vaporized the fuel before the arc ignited the vapors.

Table 1-1
Ignition Threat Operations Above a Fuel Spill on Concrete

Ignition Source	JP-4			JP-8		
Acetylene Cutting						
Arc Welding						
Disc Grinder				NI	NI	NI
10,000V Arc 1 inch Above Spill			X	NI	NI	X
10,000V Arc 3 inches Above Spill	NI	NI	X	X	X	X

NI = No Ignition X = Did Not Test



Figure 1 - 2

Fuel was spilled at one GPM from the fuel nozzle located five feet above the concrete surface onto an electric exhaust fan motor, a 500W halogen lamp (shown in Figure 1-2), and a 1500W electric space heater. Fuel temperature was 84°-87°F for these tests. The electric exhaust fan motor blade was disabled for the test. The motor was turned on immediately before the test started. Neither JP-4 or JP-8 ignited in this test. The 500W halogen lamp and the 1500W space heater were turned on to full power five minutes before fuel was spilled onto these items to give each time to warm up. Again, neither JP-4 or JP-8 ignited these two items. An additional three tests with the 1500W space heater were conducted with each fuel. The heater was placed in a one-half gallon fuel spill. There was no ignition in any of the tests.

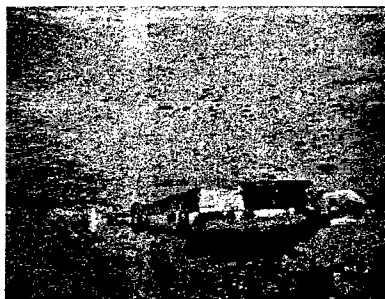


Figure 1 - 3





An electric Dremil tool was tested in two configurations. The tool was operated three times for each fuel in the middle of a one-half gallon fuel spill on concrete as in Figure 1-3, and it was tested two times for each fuel after one-quarter gallon of fuel was spilled onto the tool. Fuel temperature was 84°-87°F for these tests. The Dremil is a rotating electric tool that contains brushes. These brushes produce mechanical sparks that are a possible ignition source. The tool was placed in the spilled fuel and operated for two minutes in each test and then the tool was cycled on/off five times. No ignition occurred for each fuel tested. After one quart of JP-4 was spilled onto the tool, it was turned on and the fuel ignited immediately. A different Dremil was used for three additional fuel spill tests. The fuel was spilled onto the Dremil, and there was no ignition in one test conducted with JP-4 and two conducted with JP-8.



Figure 1 - 4

An 110V electric pump motor (Figure 1-4) was tested for ignition in one-half gallon fuel spills and with fuel flowing onto the motor. Fuel temperature was 86°-87°F for these tests. This pump motor was tested as a typical non-explosion proof AC electric motor. The pump motor was operated for two minutes in a one-half gallon fuel spill, then the motor was cycled on/off five times before the test was terminated. The fuel did not ignite in JP-4 or JP-8 during these tests. Fuel was dripped onto the pump motor at 0.2 GPM for two tests with each fuel. The motor was operated during these tests for four minutes and then the motor was cycled on/off five times before the test was terminated. The JP-8 fuel did not ignite during these tests, however JP-4 ignited during one test when the motor was cycled on/off. This ignition was most likely initiated by mechanical sparks during motor start-up.

Table 1-2
Fuel Spilled onto Ignition Threat

Ignition Source	JP-4			JP-8		
10,000V Arc 1 inch Above Floor		X	X	 *	X	X
Electric Exhaust Fan Motor	NI	NI	NI	NI	NI	NI
500W Halogen Lamp	NI	NI	NI	NI	NI	NI
1500W Electric Space Heater	NI	X	X	NI	X	X
Electric Dremil		NI	X	NI	NI	X
110V Electric Pump Motor	NI	 **	X	NI	NI	X

* Note: Fuel on the hot electrode vaporized, generating vapors that started the fire.

** Note: Ignition occurred during motor start.

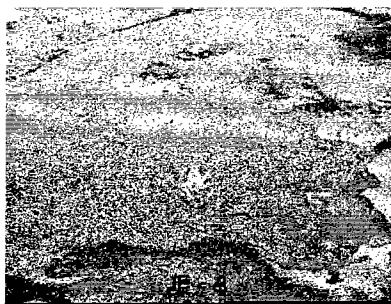


Figure 1 - 5

of the test, however due to the shallow depth of the fuel spill, the wooden match continued to burn after falling into the spill. This allowed the match to heat the fuel to its flash point where flammable vapors were given off. The vapors were then ignited by the flame. When the match fell into a pool of JP-8 at the same temperature deep enough, the match was extinguished below the fuel surface before the fuel could be heated to its flash point. JP-4, already above its flash point, would have ignited no matter the fuel depth.

Cigarettes and matches were evaluated as possible ignition sources in one-half gallon fuel spills. Fuel temperature was 85°-87°F for all tests. Ignited cigarettes were dropped into the fuel spill on concrete. The cigarette did not have enough energy to ignite JP-8 or JP-4. Kitchen matches were also ignited and tossed into a one-half gallon fuel spill as in Figure 1-5. Five matches were tossed into the fuel spill for each test unless the fuel ignited. JP-4 and JP-8 fuels ignited in all tests conducted. JP-4 ignited as expected since its temperature was well above the flash point. JP-8 was below its flash point at the beginning

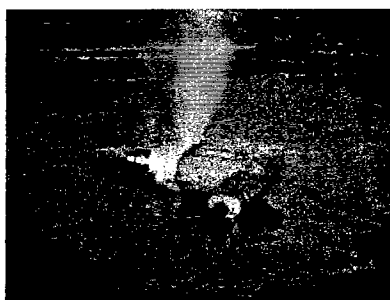


Figure 1 - 6

brushes and does not produce any sparks. The fuel spill was not expected to ignite when this drill was operated, and it did not.

Two electric hand drills were tested in JP-4 and JP-8 fuel spills for ignition characteristics. Fuel temperature was 85°-86°F for all tests. An 110 VAC electric drill was tested with its motor constantly running for two minutes and the motor was cycled on/off five times each test. A Makita cordless hand drill was tested with its motor constantly running for two minutes. The electric drill, like the Dremil tool, contains brushes which create mechanical sparks. It was tested three times in each fuel with no ignition even though the drill clearly pulled fuel into the casing (see Figure 1-6). The cordless drill tested does not use

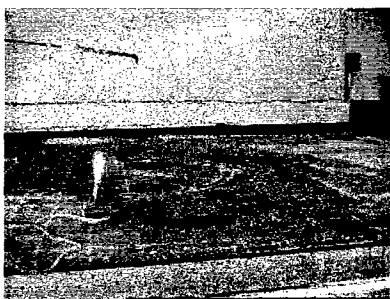











Figure 1 - 7

bulb shattered when hitting the floor. The spark generated from the bulb ignited the JP-4 fuel in each test. The spark from the bulb was not energetic enough to ignite the JP-8 fuel.

A trouble light was tested for ignition of a fuel spill when dropped from a height of five feet as in Figure 1-7. The light was turned on for each test. Fuel temperature was 85°-87°F for these tests. The light was tested three times for each fuel with the cage on that prevents the light bulb from breaking. The light was tested three times with the protecting cage off to simulate a worse case scenario that the light bulb breaks. With the cage on the trouble light, the force of impact as the light landed in the fuel spill caused the bulb to quit working in each test, but the fuel spill did not ignite. With the cage off, the light

Table 1-3
Ignition Threat Located in a Fuel Spill on Concrete

Ignition Source	JP-4			JP-8		
1500W Electric Space Heater	NI	NI	NI	NI	NI	NI
Electric Dremil	NI	NI	NI	NI	NI	NI
110V Electric Pump Motor	NI	NI	X	NI	NI	X
Kitchen Match						
Cigarette	NI	NI	NI	NI	NI	NI
Electric Drill	NI	NI	NI	NI	NI	NI
Cordless Drill	NI	NI	NI	NI	NI	NI
Trouble Light Drop (Bulb Intact)	NI	NI	NI	NI	NI	NI
Trouble Light Drop (Bulb Broken)				NI	NI	NI